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Lightweight Combat Vehicle S&T Campaign

Project Final Technical Report

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14. ABSTRACT
Lightweight vehicles are critical to the future of United States security and global U.S. Army dominance. Army ground vehicles continue to gain weight due to continually added threat mitigation technologies and despite significant S&T investments in lightweight material research and development. This report details the results of a year-long study investigating Army, academic and industrial material science programs and Army light-weighting technologies. The current materials investment portfolio requires sustained investment; there are many significant gaps inhibiting transition of these materials to vehicles. The report describes a lack of overarching lightweight requirements and oversight to help avoid performance versus weight tradeoffs. Currently, aerospace and automotive industries invest in optimization tools, experimental methods, and train their workforce to use them. Industry experts estimate that the Army is 20-25 years behind private industry in these areas. This report recommends that the Army increase investment in experimental methods to understand the fundamental physics of failure for vehicle components; establish light-weighting metrics; continue investment in supporting manufacturing technologies; and increase investment in design optimization tools, techniques, and training.

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By

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Executive Summary

The U.S. Army's future force must be more lethal, expeditionary, and agile, with greater capability to conduct operations that are decentralized, distributed, and integrated. TRADOC set a target to develop a lightweight, 35-ton expeditionary combat vehicle that will have tank-like capability and a low logistical footprint. As the Army modernizes its combat vehicle fleet to maintain a global presence, the impacts of vehicle weight on mission performance are under increased scrutiny. The need to be expeditionary to project long-distance military power drives the need for a lightweight combat vehicle force with smaller deployment, employment and sustainment footprints. Historically, weight has had a positive correlation with combat vehicle survivability; yet high vehicle weight also decreases the fleet's ability to be expeditionary, limits global mobility, increases cost, and challenges sustainment. In addition to increased fuel consumption rates and logistical support requirements, heavier vehicles are more difficult to transport by air. Anti-Access Area-Denial (A2AD) may also drive the need for greater mobility via airlift into potentially austere airfields as opposed to standard Aerial Ports of Debarkation (APODs). Transport aside, the deployment and employment footprints are to a great degree influenced by the required sustainment footprint, or support "tail," which is partly driven by weight. Put simply, large vehicles require more resources to use, maintain and sustain. Therefore, the U.S. Army Research, Development and Engineering Command (RDECOM) community, led by the Tank Automotive Research, Development and Engineering Center (TARDEC), investigated and identified a set of processes, tools, technologies and materials for vehicle light-weighting and developed a plan called the Lightweight Combat Vehicle Science and Technology Campaign (LCVSTC).

Path Forward / Overarching Recommendations

This campaign plan, initiated in October of 2013, identifies the weight reduction available through material substitution approaches and develops recommendations for Army investment in science and technology (S&T). The goal: Identify materials and required technologies which can be used to design a future 30-ton infantry fighting vehicle (IFV) and a 35-ton main battle tank (MBT) in 2030 with similar capabilities and functionality of the current systems. An RDECOM-wide working group spent one year assessing the magnitude of weight reduction possible through state-of-the-art materials research, and the likelihood of achieving the weight goal by 2030. The team studied current Army S&T investments, in addition to investments by other government agencies, industry, and academia, through reviews of prior lightweight material studies, team discussions, and a lightweight materials workshop conducted in July 2014. Here, non-Army technical experts were asked to highlight gaps in the current S&T portfolio. Due to the varying material needs across vehicle platform subsystems and components the workshop participants were broken into four sections: Armor & Structure, Automotive / Mobility, Armaments, and Electronics / Sensors / Other. The assessment verified that the Army is on the right path and no fundamentally new materials, manufacturing or design approaches were uncovered that we weren't already investigating. However, there are still challenges which need to be addressed.

Over the past 30 years the Army has reduced a specific KE armor weight by 60%, but increased threat lethality resulted in a net increase in combat vehicle weight. One key challenge is that without focused intervention, the lethality curve will continue to outpace armor development and associated weight, making vehicle weight unsustainable without some sort of concerted intervention. Focusing on the problem, we are now challenging ourselves to reduce the weight of the entire vehicle by 40% (2/3 of the previous leap in armor) in half this time, 15 years. To do this we are looking at current and supplemental investments in transformational material science efforts, such as energy coupled to matter, new material mechanisms, advanced experimental and diagnostic capabilities, and design optimization. The study also highlights industry and other agency successes using modern methodologies, where and what to leverage, and the power of new design and manufacturing approaches to fully utilize advanced materials.

The complexity of the material science challenge involves understanding the relationship between five variables: material type, its molecular structure, the application of the material (i.e., iPhone or Tank), material treatments (heating/cooling), and material processes that alter the molecular structure. MEDE, an Army program, is describing the interrelationships of these variables in extreme dynamic environments (e.g., blast) to inform material designs and applications through an Integrated Computational Materials Engineering (ICME) process. ICME is an approach to design products, their materials, and the manufacturing processes by linking material models at multiple length scales. The challenge to the research and academic community is to accelerate the adoption and pace of ICME activities and develop functionality/use cases that optimize the integration of all five complex variables in order to achieve significant material weight savings.

Computational approaches and predictive tools will reduce discovery-to-delivery cycles and optimize design trades. Continued engagement of the scientific community will continue and includes engagement with the National Materials Advisory Board. The overarching recommendations for the Army are as follows:

Weight Reduction – Not just Material Science Issue

The barriers to lighter-weight combat vehicles are significant and involve more than simple technological or material substitutions. Other barriers, beyond the scope of this report, include the long acquisition cycle, the tendency toward incremental design changes, and the reactive nature of the defense market (i.e., threat driven with little to no market competition) as compared to the proactive nature of the commercial market (i.e., defined market landscape with competition). In addition risk aversion to the introduction of new technologies due to cost and schedule implications mitigates opportunities for weight reduction, because most opportunities for weight reduction come from advancements in new technologies. These include adaptive and cooperative protection, advanced lethality (e.g., including disruptive energetic), and advanced materials (e.g., energy coupled to matter which creates a desired materials response). These technologies combined with design optimization, advanced manufacturing, and new concepts offer the highest probable path to meeting the light-weighting goals.

The Army can also take other actions to improve the possibility of weight-reduction solutions transitioning to current and future vehicle platforms. To be successful, the solutions rely not only on weight-reduction technology by itself, but ultimately on improving the organizational ability to transition lighter-weight components or other solutions to a fielded system. The following recommendations should be considered for immediate action so that future programs can successfully reduce vehicle weight.

1. Utilize an existing Army-wide governing body with a Board of Directors (BoD) to ensure purposeful focus on light-weighting Army combat vehicles. Examples include the Council of Colonels, Warfighter Technical Council or the Combat Vehicle BoD. We recommend the Combat Vehicle BoD.
    - The BoD shall be independent of any program of record (POR) or organization and should include representatives from the User, S&T and acquisition communities including TRADOC, TACOM ILSC, PEO GCS, and RDECOM.
    - The BoD will ensure high-level engagement and participation in the National Network on Manufacturing Innovation (NNMI) hubs, and work to ensure that the hubs provide value for the Army. NNMI hub engagement is also expected to reduce the 7- to 10-year window between material development and transition, by helping the material developer community understand physical requirements during the development process. The BoD's first task shall be to establish a charter, including how they will ensure that industry materials, manufacturing, design methods, and joining investments are leveraged to the maximum extent possible for use by the Army.
    - The BoD will establish a Cross Organizational Team (COT) to execute the recommendations within this plan. Specifically this team will: 1) Develop the Army's design optimization process; 2) Coordinate with Army programs and include the decomposition and individual loading requirements for each vehicle sub-component and system; 3) Coordinate and develop associated metrics; 4) Synchronize lines of effort with targeted milestones for concepting and research; 5) Capture technical achievements associated with user requirements; 6) Actively engage with the NMAB; and 7) Develop a plan baseline with an agreed upon frame work for the way ahead.

2. The BoD and COT will publish light-weighting metrics for research, development and acquisition programs. This supports weight reduction trades throughout the vehicle lifecycle and ensures that weight will be considered as a design requirement. Overarching recommendations:
    - Empower the BoD to make decisions on trades (e.g., weight vs. performance) in accordance with technology maturation timelines and metrics at the program decision points.
    - Develop criteria that ensure weight savings is prioritized on Source Selection Evaluation Boards (SSEBs). One potential method would be to offer a cost bonus to the contractor for weight savings, the amount of which should be reflective of the Army's value of weight savings as determined by the developed metrics.
    - Continue to use Systems Engineering practices and tools to understand weight saving trades against other requirements. Specifically:

- Maintain weight as the primary focus and not trade weight for performance.
- Use or develop operational metrics to determine the relative benefit of weight savings on performance versus other criteria such as transportability/ton, fuel consumption/ton, fording/ton, and reliability/ton.

Design Recommendations

1. Continue investment in programs like Materials in Extreme Dynamic Environments (MEDE) for creating materials on demand and provide input to Integrated Computational Materials Engineering (ICME) ballistic material programs.
    - Knowledge of the physics of deformation and failure under ballistic and blast loads developed under MEDE will enable the Army to create predictive models for materials response.
    - Of importance is the integration of manufacturing techniques along with the improved understanding of fundamental physics and specific loading conditions of sub-components. These S&T investments will help the Army develop specific materials to meet specific loading needs for specific vehicle components. Such precise knowledge of materials and loading needs are crucial for the application of light weighting design methods and weight-savings techniques. While some subsystems of ground vehicles are well defined, others currently lack the understanding needed to drive a weight optimized solution.
    - Continue development of canonical models to permit the difficult technical problems to be broken down into the scientific phenomena of most importance in a manner that can be studied more efficiently than an actual military design (e.g., how materials fail vs. how an armor package performs). This not only addresses the scientific portion of the problem, but also facilitates sharing in an unclassified format that permits the Army to tap into new sources of knowledge that may not be part of the Army's traditional industry base.

2. Immediate and continuing investment in building an Army core competency in design optimization for weight reduction using commercially-available design tools.
    - Design optimization will enable the creation of multifunctional and tailored components using advanced materials and varying geometries (Material and geometry are intimately connected and cannot be separated).
    - Establish a near- to mid-term goal of improving Army understanding of fundamental material and component failures under load conditions unique to the Army, enabling the optimization of existing components. For Example: automotive experts at the workshop estimated that the Abrams road arm weight could be reduced by 50% via current optimization methods; that is, by removing mass where it is not needed, and placing the right materials at the right location in the design.
    - Invest in and utilize optimization tools and processes currently used by industry to achieve significant weight savings with current materials. If cost assessments are made at the vehicle level instead at the sub-component level (as is current practice), the use

of more advanced (and expensive) materials and manufacturing could potentially be cost-neutral. This is not done currently because we do not have vehicle-level metrics by which to assess trades. The value of the multifunctional materials, which can maximize performance and cost at the system level, is often masked by present-day focus on the subcomponent level and not the system level.

- Enhance and enable vehicle concept studies through improved material performance and design detail. This will contribute to future optimization studies and enable identification of light-weighting opportunities more rapidly.

3. Investigate the relevance of Operational Energy models & metrics, and use if warranted, to better understand the impact or outcome of light-weighting materials and design strategies. At minimum, we need to have and maintain an understanding of the major weight breakpoints or trades associated with deployment, employment and sustainment footprints. Couple these results with life-cycle cost metrics to support the development of long term metrics that convey the long term advantages of lightweight combat vehicles. These metrics can then be used to evaluate candidate technologies for integration and to focus cost-effective light-weighting R&D investments.

4. Incentivize Program Management Offices (PMOs) to encourage lightweight technology insertion on currently-fielded platforms prior to the formal identification of a requirement. This change from current practice will reduce risk to new systems and accelerate material and manufacturing development. Cost metrics developed for weight reduction, along with the future return on investment will drive the threshold for determining whether or not to integrate lightweight technologies early. The team found that the science of lightweight technologies could be advanced by integrating some technologies before being supported by a business case, as illustrated by Boeing (aerospace industry). This allowed the industry to increase confidence in the lightweight technology and speed adoption.
   - Leverage RDECOM-TARDEC Combat Vehicle Prototype (CVP) effort to develop cost-informed light-weighting metrics and validate the approach. This builds design confidence for the User and technical communities while enabling quantification of weight savings for the 2030 Infantry Fighting Vehicle (IFV) and Main Battle Tank (MBT).

5. Provide and promote the opportunity for using prototype demonstration vehicles and experimental laboratory-demonstrations to drive technology advancement. This includes virtual and/or experimental components, systems, and assemblies of systems for the purposes of assessing assemblies of multiple low TRL laboratory concepts or low TRL concepts mixed with higher maturity systems. Investments in these demonstrations will drive the implementation risk of new technologies down and lead to the vehicle concepts adopting “major changes” incubated from a clean sheet of paper.
   - Utilize current real-time tools to engage the User on fielding of new technologies and designs. The User involvement should be beyond personnel engagement and include toolsets with the ability to assess the impact of individual or combinations of low TRL concepts on the end item performance and combat effectiveness from a user

perspective. One example of this is the use of a data-interface exchange model such as a Computer Assisted Virtual Environment (CAVE) to provide a real-time concept review in combination with operation/maintenance assessments made by the User.

Materials Recommendations

Armor & Structure

1. Predominant hurdles in transitioning lightweight materials to armor and structure do not lie in the materials science research; but rather in the M&S and manufacturing technologies required. In the near term, maintain current research investment in Materials in Extreme Dynamic Environments (MEDE); leverage and influence national ICME and Materials Genome Initiative (MGI) programs; and enhance design optimization core-competency efforts to define mid- to long-range material and manufacturing investments. MEDE will promote physics based understanding and predictive model creation. Recommendations for specific material investments are provided in the Armor & Structure section of this report, and include continued long term research in nano-materials, self-healing /diagnosing materials, multi-functional materials, and environmentally acceptable materials. The application of materials to armor systems will require threat-specific trades.

Automotive / Mobility

1. Enhance investment in design optimization programs in order to better quantify the potential for weight savings; and in the near term, leverage materials being developed within the automotive industry and Department of Energy Vehicle Technology Office (DoE VTO). Recommendation for specific material investments is included in the Automotive/Mobility section of this report.

2. Invest in far-term Automotive/Mobility alternative technologies such as fuel cells and advanced suspension designs. The 30- to 35-ton weight goal will likely require use of a tracked system, but wheeled or hybrid approaches could provide additional weight savings with equivalent mobility if the technology at this weight is further developed.

3. Mandate advanced technology programs such as hydropneumatic suspension units (HSUs), cooling systems, and power-plant designs which incorporate weight reduction metrics through material optimization at the component level; allow for alternative approaches such as engine downsizing and waste heat recovery.

Armaments

1. Develop and continue multiple material technology investments to reduce gun barrel weights and recoil loads, while maintaining or improving energy-on-target metrics. Specific programs are discussed in the Armaments section; a few are shown here for reference.

- Assess the state-of-the-art in ceramics / ceramic matrix composites (CMCs) for use in gun bores to determine potential for use in the required timeframe.
- Energetic material programs to facilitate smaller munitions with similar energetics to current ammunition and higher P_h and P_k.
- Invest in advanced manufacturing of Nextel 610 fibers in cast aluminum matrices on steel gun barrels.

Electronics / Sensors / Other (ESO)

1. Continue to invest in efforts to consolidate vehicle architecture. This will enable the reduction of vehicle weight through elimination of redundant components, and the reduction of vehicle power requirements through improved semi-conductive materials. Specific materials are discussed in the ESO section. Additional investment concepts for consideration include:
    - Alternate Power Generation – Harness shock compression motion from the vehicle to power small sensors or electronics to reduce the power distribution cables.
    - Share Processing Capacity – In conjunction with common architecture and elimination of electronics redundancy, enable multiple electronics packages to share common power and processing capacity to reduce power consumption and packaging space.

Manufacturing Recommendations

In addition to the design processes and materials shown above, the team recommends S&T investments in manufacturing technologies which will support design optimization and advanced material development. Developing manufacturing processes in parallel with the material development is critical to transitioning all components. Although Army S&T investments currently support the manufacturing and joining of materials, for the future, the Army must ensure that manufacturing programs are put in place to support emerging materials. Key recommendations in manufacturing:

1. Increase investment in advanced manufacturing and joining technologies for emerging materials through manufacturing technology (ManTech), where external (industry, OGA, academia) investments fall short or are not aligned with Army needs. A portion of the ManTech investments should be tied to a long term strategy and strategically determined by the BOD and COT as opposed to driven by an annual investment competition. These programs, driven by ICME materials-development programs, will yield high-potential emerging materials that will require specific, parallel programs in joining and manufacturing to enable rapid transition. Additionally, these manufacturing processes would enable the utilization of advanced design optimization techniques.

2. Increase active engagement and adopt a "guiding stance" in the NNMI hubs to ensure that the Army needs are understood and addressed by the consortia. These needs should be derived from ICME and design optimization programs. By leveraging the NNMI hubs, the Army can enable cost sharing and development of a manufacturing base that can support the Army's future needs.

Final Thoughts

The team recommends that the Army invest in advanced manufacturing processes, design optimization tools/expertise, and material science as outlined above. Assuming these S&T investments are made, and using current weight reduction estimates for advanced material performance, the projected weight for a future (2030) MBT is estimated to be 45-49 tons, and the future IFV weight is estimated to be 29-31 tons (see Table 1, below). The IFV met the weight reduction goal of 30 tons, yet this weight reduction assumes a great deal of risk on research programs. Unfortunately, when only material science solutions, processes and technologies are applied to the MBT, the estimated achievable weight totals 45-49 tons which is still far above the goal of 35 tons. In order to meet the MBT 35-ton goal, changes such as crew size, automation, the use of adaptive protection technologies, and clean-sheet vehicle designs, informed by advanced concepts, such as the Next Generation Close Combat Vehicle (NGCCV) study, will be necessary. Constant engagement with the User is required with these advanced concepts, not only for design and capability, but also for any possible changes in doctrine.

Table 1. Evaluation of 2030 MBT and IFV vs. 30 ton weight reduction goal.

	Weight Achievable w/High Risk [Tons]	Goal Weight [Tons]	% above or below goal
Projected Weight MBT	45-49	35	29% above goal
Projected Weight IFV	29-31	30	3% below goal

The NGCCV study, to be completed in October 2014, highlights technologies and concepts that will further reduce vehicle weights, but require doctrinal changes. Some of the technologies from the NGCCV study are briefly discussed in this report. However, a full assessment of future MBT weight under the given requirements of this study requires the development of a complete vehicle design. This MBT concept study could be rolled into the Army's Future Tank study. Other technologies, such as modular and adaptive protection, require designing vehicles and structures to separate the A-level structure from the armor and protection systems. The team believes that modular protection is scalable, allowing future armor upgrades and easing future protection technology integration, while also supporting the development of localized structural reinforcements as capabilities are added. However, this capability must be compared to operational and cost metrics since modularity generally incurs a weight penalty and has potential logistics issues.

Finally, as a holistic approach to light-weighting, the following graphic (Figure 1) illustrates how the Lightweight S&T Recommendations can tie into advanced operational and concept models and vehicle-specific M&S. This would provide a holistic Army approach to ground vehicle weight reduction, and could then be used as part of a cyclical process (e.g., recommendation #5 on p.10). The holistic light-weighting approach would be an integral part of future ground vehicle concepts and optimization studies, direct future force vehicle studies and concept vehicle iterations, and help determine what variables will enable the Army to become more expeditionary. This strategy has been executed on a small scale with the FY14 NGCCV study, and will be continued in accordance with the Advanced Combat Vehicle Capability Development Strategy highlighted in Figure 1.

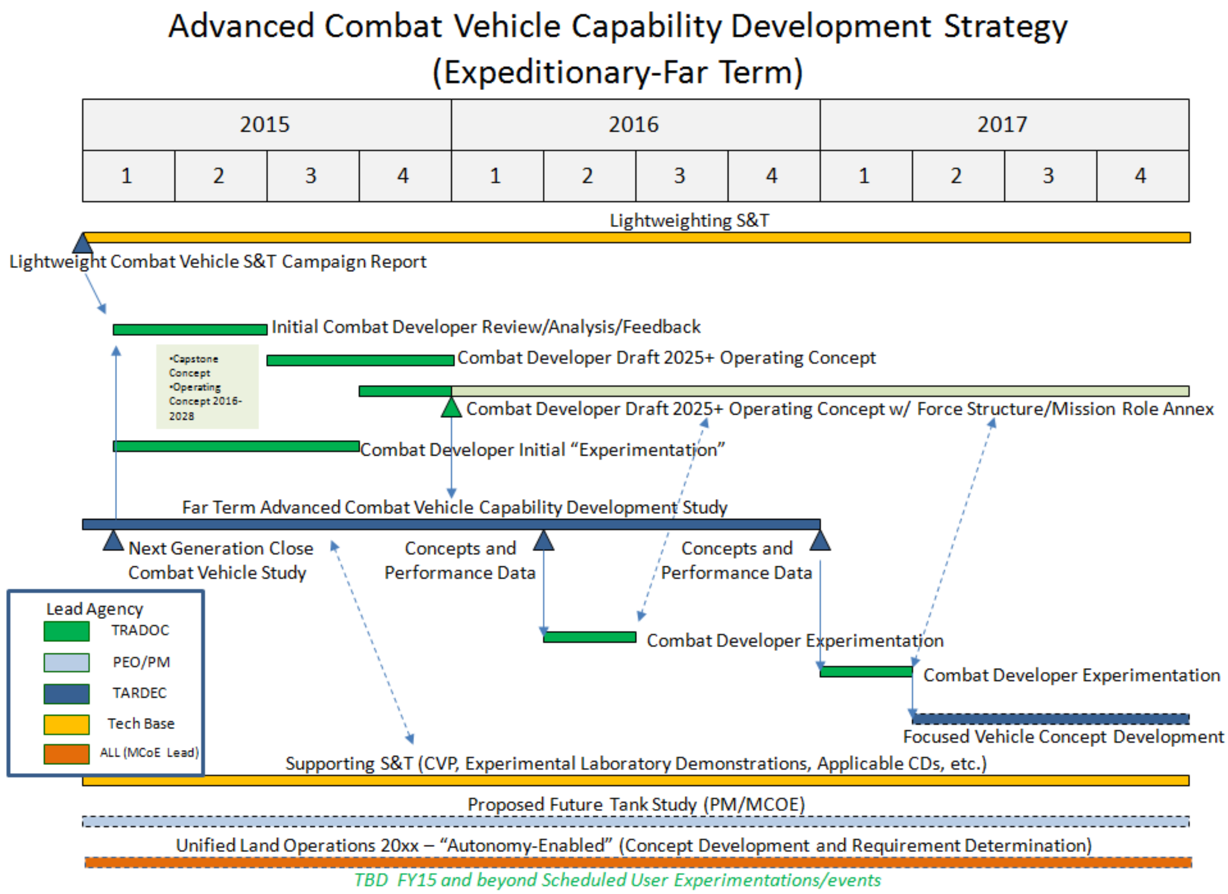

Figure 1. Advanced combat vehicle capability development strategy.

The chart below (Figure 2) shows the establishment of a Board of Directors to govern the recommendations in this report and to optimize S&T investments across the five overall light-weighting lines of effort (Armor & Structures, Automotive / Mobility, Armaments, Electronics / Sensors / Other, and non-material science approaches to light-weighting). The Board of Directors will make decision trades in accordance with technology maturation timeframes that are further integrated into the plan and depicted as decision points. Overarching Army design optimization and ICME investments are also laid out, along with the top level investment areas and general weight savings for each vehicle subgroup. The weight reduction estimates include current S&T investments and the recommended S&T investments.

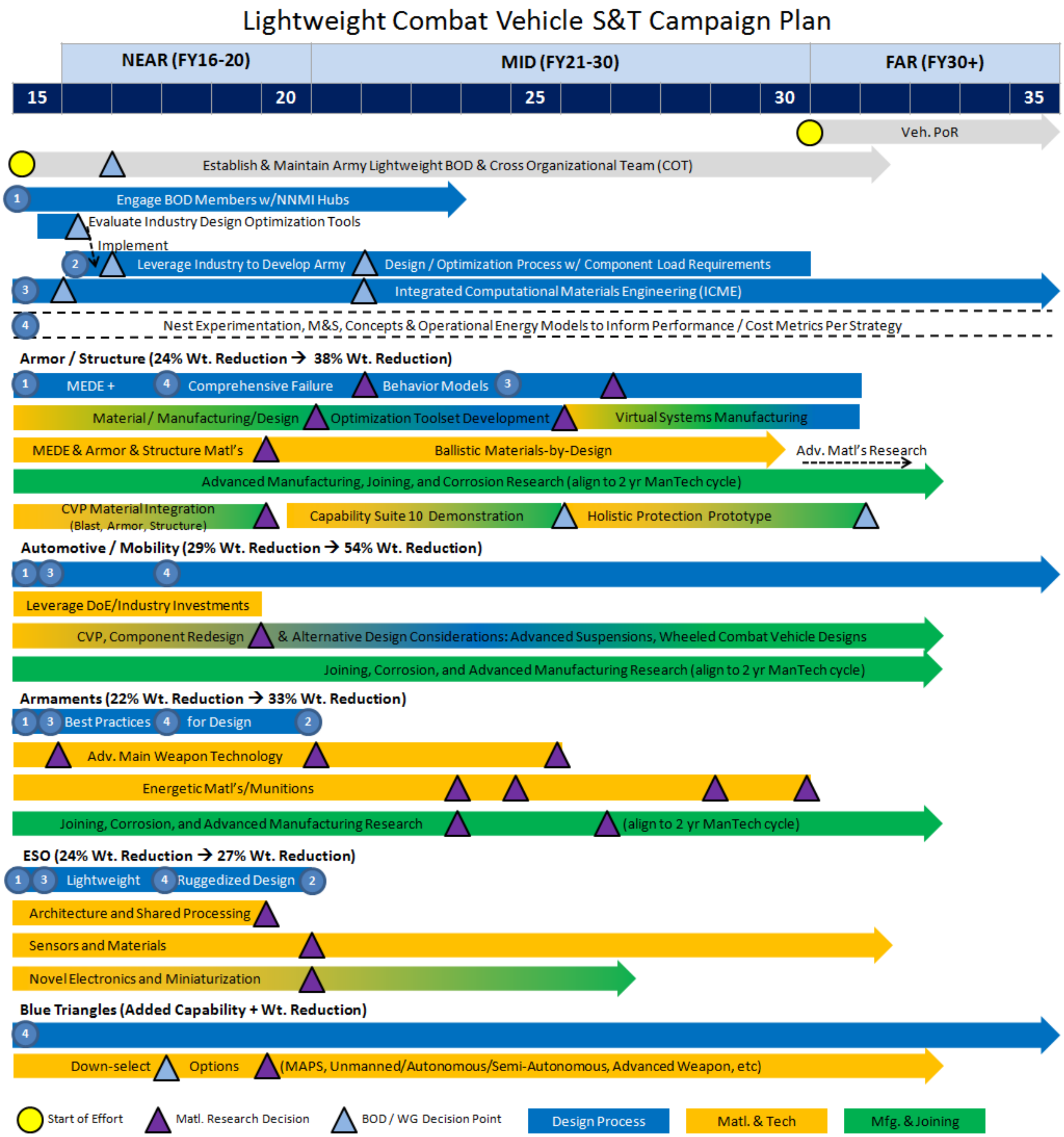

Figure 2. LCVSTC plan

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This report is the result of extensive collaboration. It has been reviewed in draft form by workshop sub-group facilitators, a group chosen for their expertise in materials and military system requirements. These subject matter experts (SMEs) facilitated the workshop sub-groups and summarized their results as report sections for inclusion into this report. The review comments and draft manuscript materials remain confidential to maintain and protect the process integrity. Additionally, this report was staffed for comments in draft form to RDECOM, ASAALT, PEO-GCS, and TRADOC (ARCIC and MCOE).

List of Figures

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List of Symbols, Abbreviations, Acronyms

A2AD	Anti-Access Area-Denial
AoA	Analysis of Alternatives
AHSS	Advanced High Strength Steel
ALMMII	American Lightweight Modern Metals Innovation Institute
AMAS	Autonomous Mobility Appliqué System
AMO	Advanced Manufacturing Office (DOE)
AMRDEC	Aviation and Missile Research, Development and Engineering Center
APG	Aberdeen Proving Grounds, Maryland
APOD	Aerial Ports of Debarkation
AReS	Advanced Reconfigurable Spaceframe Demonstrator
ARCIC	Army Capabilities Integration Center
ARDEC	Armament Research, Development and Engineering Center
ARL	Army Research Laboratory
ALVM	Army Lightweight Vehicle Materials
ATEC	Army Test and Evaluation Center
AVPTA	Advanced Vehicle Power Technology Alliance
CAVATD	Composite Armored Vehicle Advanced Technology Demonstrator
CAV-IHS	Composite Armored Vehicle Integrated Hybrid Structure
CERDEC	Communications-Electronics Research, Development and Engineering Center
CIFV	Composite Infantry Fighting Vehicle
CMC	Ceramic Matrix Composite
CONWEP	Conventional Weapons
COT	Cross Organizational Team
CotS/COTS	Commercial-Off-the-Shelf
CVP	Combat Vehicle Platform
DIB	Defense Industrial Base
DoB/DOB	Depth of Burial
DoA	Department of the Army
DoD/DOD	Department of Defense
DoE/DOD	Department of Energy
EoS/EOS	Equation of State
FCS	Future Combat System
FEA/FEM	Finite Element Analysis/Method
FPA	Focal Point Areas
FSI	Fluid Structure Interaction
GFE	Government Furnished Equipment
GHULL	Generic Hull (as in TARDEC Generic Hull)
GPS	Global Positioning System
HME	Home-Made Explosives
HMMWV	High Mobility Multi-purpose Wheeled Vehicle

HSU	Hydropneumatic Suspension Unit
ICME	Integrated Computational Materials Engineering
IED	Improvised Explosive Device
IFV	Infantry Fighting Vehicle
IRAD	Independent research and development
LCVSTC	Lightweight Combat Vehicle Science & Technology Campaign
LFT&E	Live Fire Test and Evaluation
MBT	Main Battle Tank
MCoE	Maneuver Center of Excellence
MD	Maryland
MEDE	Materials in Extreme Dynamic Environments
MGI	Materials Genome initiative
MMJ	Multi-Material Joining
NAP	National Academies Press
NGCCV	Next Generation Close Combat Vehicle Study
NNMI	National Network on Manufacturing Innovation
NRC	The National Research Council
OEM	Original Equipment Manufacturer
OGA	Other Government Agency
OSD-DDR&E	The Office of the Secretary of Defense – Director of Defense Research & Engineering
P_h	Probability of hit
P_k	Probability of kill
POC	Point of Contact
PM	Program Management Office
PSM	Prescribed Structural Motion
R&D	Research & Development
RDECOM	Research, Development and Engineering Command
RDT&E	Research, Development, Test & Engineering
RDTA	Reliability Development and Test Article
RF	Radio Frequency
RHA	Rolled Homogeneous Armor (steel)
RO	Reduced Order (as in simulations)
S&T	Science & Technology
SEP	System Enhancement Package
SME	Subject Matter Expert
SSEB	Source Selection Evaluation Board
SiC	Silicon Carbide
SimBRS	Simulation-Based Reliability and Safety
SLAD	Survivability and Lethality Analysis Directorate
SPH	Smooth Particle Hydrodynamics
SW	Software
TARDEC	Tank Automotive Research, Development and Engineering Center
TRADOC	U.S. Army Training and Doctrine Command

T&E	Test & Evaluation
UBM	Underbody Blast Modeling/Methodology
ULV	Ultra Light Vehicle
VICTORY	Vehicle Integration for C4ISR/EW Interoperability
VECTOR	VICTORY Enabled Company Transformation
VTO	Vehicle Technologies Office (DOE)
WD	Work Directive
WMRD	Weapons and Materials Research Directorate

Introduction

The Challenge

COL Christopher Cross, TRADOC-ARCIC, stated during the Lightweight Materials Workshop that the Army desires a 35-ton Combat Vehicle. This need for a lightweight combat vehicle stems from the need to be expeditionary. Being expeditionary ensures that the Army retains operational advantages while increasing global, operational, and tactical mobility, by improving Army global responsiveness and its ability to project forces, conduct forcible and early entry, and transition rapidly to offensive operations to ensure access and seize the initiative. The Army future force must be leaner, more lethal, expeditionary, more agile, and have greater capability so that it can conduct decentralized, distributed, and integrated operations. [1, 2] TRADOC-ARCIC is working diligently to understand the materials investment portfolio with the goal of realizing improvements greater than an order-of-magnitude (54%) weight reduction for combat vehicles by 2030, and to understand how to make the appropriate trades to reduce weights while not sacrificing performance.

Military threats and protection technologies advance in concurrent and cyclical manner as reactions to each new and emerging threat. During the 1980s and prior, vehicles experienced primarily frontal threats (Figure 3). As we progressed into the 2000s, vehicle systems started to experience threats approaching from a hemispherical direction; that is, the top of the vehicles now needed protection. These new armors increased the weight of the vehicle and loads imparted to the structure. As the Global War on Terrorism progressed into the 2010s, vehicles began experiencing threats from all angles, creating a need to protect the vehicle and its occupants in full 360-degree spherical fashion.

As each new threat type necessitated the need for a new or modified armor solution, vehicle weights continued to grow despite significant and continued investment in materials, technologies and methods to reduce armor weights. One key challenge is that without focused intervention, the lethality curve will continue to outpace armor development and associated weight, making vehicle weight unsustainable without some sort of concerted intervention. Increased weight due to increased protection results in larger (and heavier) powertrains, which necessitate larger cooling systems, stronger (and heavier) suspensions, and so on resulting in an upward spiral of weight increase.

Figure 3. Reducing vehicle weight vs. increased threats.[3]

As the Army modernizes its combat vehicle fleet to maintain a global presence, the impacts of vehicle weight on mission performance are under increased scrutiny. Weight historically has had a positive correlation with combat vehicle survivability. Yet high vehicle weight contributes negatively to the fleet's ability to be expeditionary, increases fuel consumption rates, and contributes to increased logistical support: large vehicles require more resources to move them.

Recent vehicle design programs such as Future Combat System (FCS) and Ground Combat Vehicle (GCV), attempted to increase capability, but often accepted increased weight as advanced fighting technologies were integrated. For current systems, Space, Weight and Performance (SWaP) are traded continuously as systems gain weight through the addition of new technologies to counter emerging threats. Further, the weight spiral (positive or negative) is often not considered in its entirety as weight is traded.

For all these reasons, the Army must pursue the identification of materials and technologies for light-weighting as part of our S&T strategy to support the needs of the future force. An expeditionary combat fleet with low logistical footprint is critical to ensuring the Army's future success.

The Lightweight Materials Campaign (Methodology)

Unlike prior material studies, this is the first holistic look at a vehicle system coupled with a material science S&T plan for the Army. In an effort to address the needs for a lightweight future combat force, the Army developed a plan to investigate the state-of-the-possible in material and technology programs that could support a lightweight combat vehicle program in 2030, while maintaining current vehicle capabilities and design. The technologies considered fell into one of two major categories: (1) Material and technology programs that would directly reduce vehicle weight, and (2) Technology programs that would provide an indirect, or secondary, weight reduction. An additional requirement for the material technologies was that they would reach Technology Readiness Level 4 (TRL 4) (see Figure 4) between 2021 and 2030. With this restriction, we assessed the level of weight reduction possible through material science approaches, and are reasonably confident that the materials and technologies identified in this report would mature to TRL 6 and transition to the future programs of record in a timely fashion.

Technology Readiness Level (TRL)	Description
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3. Analytical & experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.

Figure 4. Definitions of Technology Readiness Levels (TRLs).[4]

The following definitions of near-, mid- and far-term are utilized throughout this report:

Near-term: Current year to 2020
Mid-term: 2020-2030,
Far-term: Beyond 2030.

A baseline assessment was conducted to better understand the weight distribution of current combat vehicles, and the magnitude of the challenge. The Abrams M1A2 SEP and Bradley M2A3 were selected as the baseline set of capabilities with which to drive to the 35- to 30-ton weight goals (see section: Baseline Subsystem Weights & Programs). In addition, a review of past studies was also conducted (see section: Previous Studies Analysis).

A cross-RDECOM team (including ARL, TARDEC, CERDEC, ARDEC, and AMRDEC) worked to identify all Army S&T investments focused on material science and technologies that could reduce vehicle and system weights. This team identified funded, unfunded, and past programs in all areas of vehicle performance, such as mobility, survivability, and lethality. Programs identified covered material science, manufacturing, joining/assembly methods, vehicle design/architecture, and weight mitigating/avoidance technologies. Team members met monthly to discuss investment portfolio specifics of their organizations. Additionally, the team identified relevant programs across academia, industry, and government offices outside the DoD that could be leveraged for inclusion into a cohesive weight reduction plan for Army combat vehicles. These organizations were then included in the monthly meetings and presented their relevant programs.

To fill gaps identified within the portfolio, the team held a workshop on 29-31 July 2014 at Aberdeen Proving Ground (APG), and hosted by ARL. Leaders and experts from other government agencies,

industry, academia provided input on innovative methods and material development processes that the Army can leverage to meet its weight reduction goals.

The results of the baseline study, the analysis of past studies and S&T investments, the views of internal and external experts on current investments and future investments from the team and the workshop were summarized in a draft report. The draft report was submitted for review and comment to relevant Army organizations. The comments were then incorporated into this final report.

Previous Studies Analysis

The Lightweight Combat Vehicle Science & Technology Campaign (LCVSTC) is the first attempt to quantify the impacts of specific material investments to a vehicle system (or sub-system); and this study is also the first attempt to allow the User community to see inside the science and collaboratively identify a path forward toward reducing combat vehicle weights. The team developed specific application and weight-reduction estimates, which are presented in the sub-sections for Armor & Structures, Armaments, Automotive / Mobility, and Electronics / Sensors / Other materials. This also demonstrated the Army's ability to effectively integrate these sub-systems into a holistic vehicle design.

As a key part of LCVSTC development, the team reviewed numerous high-level studies relating directly to Defense systems and light-weighting materials. These reports consistently identified the same technological gaps; often making similar recommendations for investigation of areas consistent with the findings of the LCVSTC workshop.

During the Lightweight Materials Workshop in July 2014, the participants raised many of the recommendations from these prior reports as continuing issues which still require investment. Workshop participants determined that many of the materials presented in the following sections are unlikely to be ready for integration into vehicles until after 2025; however, they will still be considered and the BoD will make investment decisions related to their potential contribution for the long term. Emphasis will be on design and manufacturing optimization techniques used in non-defense industries, process control, and material scale-up procedures for the short term. The list of materials for continued long term research includes nano-materials, self-healing /diagnosing materials, multi-functional materials, and environmentally acceptable materials.[5]

The 2003 National Research Council (NRC) report *Use of Lightweight Materials in 21st Century Army Trucks* provided the following table of materials opportunities, identifying short-, mid-, and long-term opportunities in truck-specific sub-systems (Figure 5). These opportunities are a near-perfect overlap with gaps in current material research identified by participants at the Lightweight Materials Workshop. This provides some confidence that the industrial material investment portfolio described in this report is aligned well to Army needs and raises the likelihood of both affordability and transition. One important caveat is that supporting S&T investments must be made in the manufacturing processes, experimental high strain-rate validation, and design optimization process tools. Without these S&T investments, these materials may not transition to combat vehicles due to the extreme physical requirements experienced by combat systems.

Subsystem	Short Term	Medium Term	Long Term
Frames	High-strength steels, stainless steels, galvanic insulation, corrosion-resistant coatings and design	High-strength steels, hydroformed tubes to replace frame rails, truss frame to replace frame rail/ladder construction, and extend benefits to secondary structure	Magnesium castings, PMCs, light modular structures, and embedded sensors.
Secondary structural elements	Stainless steel (truck cabs), aluminum alloys (truck cabs, cargo beds), superplastically formed aluminum (cab structures), magnesium extrusions (passenger seat frames), sheet molding compound (cab components), tailor-welded blanks (door panels), and corrosion design.	Ultrahigh carbon steels (side impact panels), aluminum 2519 (forged and extruded for use in armor plate), magnesium (body and closure components, seats, front and rear backs), PMCs (truck boxes, side panels, cab structures), multifunctional materials for truck cabs (combine armor and structure), electromagnetic joining, adhesive joining, and friction stir welding.	Titanium (armor plate), smart materials, embedded sensors, self-repair, energy storage, and ballistic protection.
Structural drivetrain	Aluminum alloys (driveshafts), magnesium castings (transmission casings and transfer cases), MMCs (brake drums and rotors), PMC springs for light trucks, and corrosion-resistant coatings.	High-strength steels, magnesium alloys (transmission, transmission case and cover, engine block, suspension components), MMCs (powertrain, brake, wheels), PMCs (driveshafts, springs for heavy trucks), high-performance castings, titanium springs, and higher-performance tire cord.	Titanium springs, embedded sensors, additive metal process technologies (parts on demand), and electric/hybrid drivetrains.

Figure 5. Truck Subsystem material application vs. expected transition time frame (Near/Mid/Far).[6]

Another significant hurdle to light-weighting is that the defense community has difficulty explaining material requirements in an unclassified manner, a concern also echoed in the previous reports. Specifically, there is a need for "canonical models that translate armor system requirements (often with data restricted access) into characterization mechanisms that an open research community can use in designing new lightweight protection materials."[7] The lack of these experimentally validated models inhibits the ability to adopt optimization and analysis methods and prevents material developers from synthesizing materials able to meet the extreme defense requirements.

There is also a need for sustained investment in advanced computational and experimental methods. *Opportunities in Protection Materials Science and Technology for Future Army Applications* advocates for the use of a new material development process paradigm shown in Figure 6, which utilizes concept design methods to balance the strengths and weaknesses of a new material. The proposed process uses advanced computational and experimental methods, materials by design, ICME, improved manufacturing processes, improved material synthesis processes, and the performance of lifecycle analyses as part of a holistic cycle to develop materials specific to design requirements.[8]

This new development paradigm for the Army has strong potential to accelerate the development of armor materials[9] and will be applicable to all vehicle components, not just armor and structures. Conversations with representatives of aerospace and automotive companies such as EDAG Engineering, FEV GmbH, The BOEING Company, Dassault Systemes, and Altair, indicated that their material development and design processes work in similar manner[10]. To begin the process, industry partners typically start by understanding the fundamental physics, defining the component function and loading requirements, and determine whether or not a new material is needed. If needed, they design a material to satisfy the functional requirement. If a new material is not needed, they use optimization software analysis techniques to design specific components from existing materials. Three of the

representatives from the companies who attended the workshop stated their opinion that the Army was "20 to 25 years behind" the practices used in their respective industries.[11]

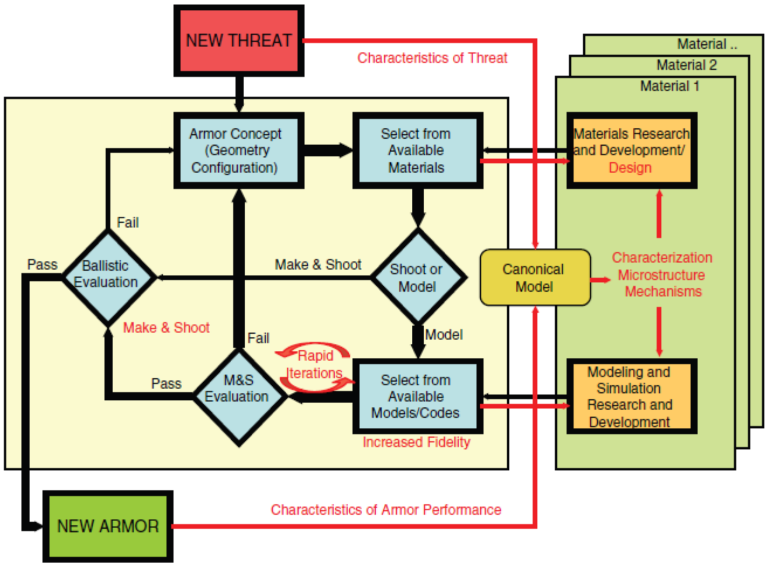

Figure 6. New development paradigm.[9]

The overarching intent of this campaign is to accelerate the transition of materials from concept into service by replacing the traditional iterative design-test-redesign-retest cycle with a new process, one heavily dependent on concept studies that are validated by modeling and simulation (M&S). An M&S-dependant process, such as ICME, is made possible through understanding fundamental material behavior combined with functional decomposition of the material application/components.[12] To be successful, ICME requires information distillable at scale and significant experimentation to validate models. Extensive databases must be developed and maintained to capture critical ICME-enabling data. This method also requires a cultural shift in that cross-functional teams must focus on common goals, the "foundational engineering problems." Nearly 13 years after one subcommittee identified the need for heavily computation-intensive methods and processes[13], recommendations are yet to be widely adopted in the United States.[14] Within the DoD; the adoption is becoming more of a reality in isolated pockets. As a result, there will be a significant time investment required to develop the supporting infrastructure, technologies and methods to enable M&S-dependent processes consistently across the DoD. Being able to lean heavily on M&S methods is a requirement to effectively propel materials development for light-weighting, and as a result, is the driving factor to realize the Army's light-weighting goals.

In addition to the review of previous strategic documents, the team also reviewed prior Army S&T programs focused on light-weighting goals. These Army S&T programs and historical trends were compiled into lessons learned and information which can be leveraged by current or future efforts or in the development of a light-weighting strategy. These previous studies provide a baseline for and have helped shape the LCVSTC plan presented here.

One historical example of a significant light-weighting effort was the M1 Abrams light weighting effort. This “paper study” was initiated due to the 70+ ton weight of the M1. This effort ranked the benefits of light-weighting approximately 50 components in order to reduce the weight of the platform. The program demonstrated how combat vehicle systems could be made lighter by looking at alternative materials.[15]

Another effort that occurred during the 1980’s was the Army Research Laboratory’s (ARL) Composite Infantry Fighting Vehicle (CIFV). The program’s ambitious use of lightweight composite materials showed that it might be possible to make a lighter combat vehicle out of composites. The success of this program spawned the Composite Armored Vehicle Advanced Technology Demonstrator (CAVATD). This effort took a holistic look at how the Army might put together a vehicle system made of composites.

The CAVATD effort represented the start of a long look at using composite and ceramic armors to improve armor weight efficiencies. The program also showed that the vehicle hull could be considered more discretely as an upper and lower system, rather than as one monolithic system. By evaluating the hull as separate upper and lower hull sections, the CAVATD team discovered a clean, if imaginary, break where composite materials versus metallic materials could be applied to more advantage. The CAVATD demonstrated that composites were more appropriate for the upper portion of the hull and metallics were more appropriate for the lower.[16]

As the CAVATD program was ending, the U.S. military was developing a new “post Cold-War” posture which involved a more adaptable, flexible, and mobile Army. There was no longer a known enemy, and thus a new strategy led to the development of the Future Combat System (FCS). This program evaluated the use of a common modular vehicle allowing the transport of vehicles that were able to change missions “on the fly” through reconfiguration. This led to major advancements in modular vehicle chassis design and also supported advancements in vehicle structure and armor as well.

A parallel effort to the FCS program was the Composite Armored Vehicle Integrated Hybrid Structure (CAV-IHS). This effort extended the CAVATD program and performed a trade study to compare spaceframe, monocoque, and spaceframe/monocoque hybrid structural designs. Based on the results of the trade study, an Advanced Reconfigurable Spaceframe Demonstrator (ARES) was developed and evaluated at the University of Nevada, Las Vegas UNLV to show the potential of a reconfigurable spaceframe.

More recent Army S&T efforts include, but are not limited to, the All Composite Lightweight Military Vehicle and the Ultra Light Vehicle (ULV) Research Prototype. The ACLMV’s objective was to develop an armor-ready lightweight composite tactical vehicle (i.e. HMMWV-like) for durability evaluation. These composite vehicles were designed and built to maintain necessary vehicle strength and durability; integrate sub structures and multi-functionality armor systems/solutions; eliminate corrosion, which in turn, reduces maintenance cost and time; increase payloads; and allow for efficient transportation in planes. The ULV effort was developed under the guidance of The Office of the Secretary of Defense – Director of Defense Research & Engineering (OSD-DDR&E) to explore and demonstrate the ability to meet the survivability of 16-20 ton tactical vehicles in a smaller 7-9 ton weight class while maintaining or improving other capabilities (mobility, transportability, fuel economy). The ULV effort utilized numerous

techniques on a variety of subsystems to meet program objectives.[17] Techniques used by the ULV program are shown below in Table 2. These included:[18]

Table 2. Technologies and Techniques used by ULV to meet weight objectives.

Technology	**Benefit**
Opaque Armor:	Multi-layered Aluminum and composite materials with steel base structure achieved an integrated protection solution on the structure (not require B-kit armor package). Equates to weight reductions compared to RHA equivalent.
Transparent Armor:	Ultra-light transparent Spinel ceramic reduces weight by almost 50% per ft^2.
Wheels & Tires:	Lightweight 2-piece forged Al rim assembly weighing 42 lbs with custom tires saved 320 lbs over a comparable program's compliant wheel and tire set.
Fewer Frame Components:	The chassis is a monocoque design, where the crew capsule is integrated into the front and rear frame members distributing the load through the entire system. There is no rolling chassis thus designing a survivable crew capsule is easier and more flexible with no frame structure to interfere with critical cab survivability designs. Both front and rear frame sections are welded directly to the steel capsule structure creating a single lightweight, rigid structure.
Planetary Geared Hubs:	Weight kept to a minimum by reducing half-shaft torque requirement, keeping each motor centrally located between each wheel set and providing high drive efficiency. Design eliminates the traditional transmission, drive shafts, and transfer case.
Brake System:	The ULV brake system is a compilation of mostly COTS components, with the exception of custom designed 380 mm carbon ceramic brake rotors saving 10 lbs per rotor over conventional steel rotors
Consolidated Vehicle Electronics/GFE:	Items were packaged in the rear of the vehicle with data routed through a single data distribution system outputting information to tablet-like displays to the driver, truck commander, and gunner positions. This attempts to reduce weight, heat, and secondary projectiles to the crew compartment while allowing for increased interior space.

This summary of prior reports and programs highlights those that are most relevant to the LCVSTC, and are listed in Appendix D: References. While there are other reports on lightweight efforts, the recommendations of each of the reports reviewed were a subset of those mentioned here. Also, given that similar investment recommendations for the Army have been made by the government and outside entities, the path forward presented in the rest of this report is of high validity within the technical community.

Baseline Subsystem Weights

Given the task of developing a materials plan to enable future vehicle programs for a 35-ton Main Battle Tank (MBT) and a 30-ton Infantry Fighting Vehicle (IFV) in 2030, a set of capabilities were selected to allow potential weight reduction estimates to be calculated. The Abrams M1A2 SEP and Bradley M2A3 were selected to provide the generic vehicle designs and capabilities desired for the future 2030 platforms. Thus, material science and technologies reviewed in this study were selected based on their ability to reduce weight while still maintaining all of the capabilities in these baseline systems. Again, this campaign is focused on future combat vehicles, and these legacy systems are being used only as design guidelines. This is not meant as a weight-reduction analysis for Abrams and Bradley.

Using the Abrams and Bradley capabilities selected as the baseline for the future combat vehicle, we broke down the vehicles into four main sub-systems that have distinct material and technology requirements. The common groupings are: Armor & Structures, Armaments, Automotive/Mobility, and Electronics/Sensors/Other Materials (ESO). Binning the vehicle component weights and Army S&T investments into these categories illustrates that most of the vehicle weight and funded S&T investments are in the areas of Armor & Structure (Table 3). The funded programs are currently part of the POM, whereas the unfunded programs are additional efforts that would support weight reduction in future combat vehicles that are either conceptual, or are not in-line with a current PoR.

Table 3. Vehicle weight and funding S&T investments across workshop breakout discussion areas.

	Abrams M1A2 SEP Weight		Bradley M2A3 Weight		Number of Programs	
	Ton	%	Ton	%	Funded	Unfunded
Armor & Structures	40.6	53 %	21.1	54 %	36	1
Armaments	11.7	15 %	3.7	9 %	33	22
Automotive/Mobility	20.2	27 %	10.7	27 %	15	9
ESO	3.8	5 %	3.8	10 %	10	5
Total	76.3	100 %	39.3	100 %	94	37

The fact that Armor & Structure represents the most sizable investment comes as no surprise to the vehicle community, where vehicle light-weighting is typically viewed as a single-point solution (i.e., go after the biggest target to realize the biggest benefit). However, the LCVSTC has extremely ambitious targets for weight reduction by 2030: Reducing the weight of a future tank from 76.3 tons to 35 tons (54% reduction), and a future IFV down from 39.3 tons to 30 tons (24% reduction). With these extreme weight reduction goals, we cannot afford to neglect the potential primary and secondary weight savings in the rest of the vehicle. Neither of these weight reduction goals could be achieved by reducing weight in Armor & Structure alone; even when spread over the entire vehicle, both goals represent a significant challenge for material science.

The remainder of the report focuses on addressing these demands at the sub-system level, identifying the programs that are currently ongoing, fulfilling gaps highlighted in this Campaign, and proposing a recommended path forward.

Non-DoD Government Programs

There are two major non-DoD government agencies that support the Army's objectives outlined in this study: The Department of Energy (DoE) and the National Network on Manufacturing Innovation (NNMI).

The DoE has two major offices that are relevant to ground vehicle light-weighting technologies: the Vehicle Technologies Office (VTO) and the Advanced Manufacturing Office (AMO). The VTO is responsible for developing technologies that reduce the energy use of the commercial light-duty automotive and heavy-duty truck industries. Since 2011 TARDEC has administered a partnership with VTO called the Advanced Vehicle Power Technologies Alliance (AVPTA), which leverages joint investment in seven major technology focal point areas (FPAs):

1. Advanced Combustion Engines and Transmissions
2. Lightweight Structures and Materials
3. Energy Recover and Thermal Management
4. Alternative Fuels and Lubes
5. Electrified Propulsion Systems
6. Energy Storage and Batteries
7. Analytical Tools

While the commonality of materials, application domain, and manufacturing processes make such a partnership understandable and appealing, it belies the difficulty posed by the differences in business and vehicle requirements between the defense and commercial industries. For example, the automotive industry uses thin sheet metal and produces 50,000 – 150,000 units/year (i.e., production number of a specific model/year), whereas Defense uses thick plates and produces 100-300 units/ year. Developing programs that are of mutual benefit requires a detailed understanding of the technologies, and constant coordination between the subject matter experts to ensure maximum benefit to both organizations. This detailed understanding has resulted in several joint projects ranging from developing non-rare-earth metals for electric motors to researching breakthrough technologies in dissimilar materials joining. However, challenges still exist, from securing additional funding to ensure parity and broaden the partnership, to developing an approach for rapid transition of these technologies to the defense industrial base.

The AMO is another DoE office responsible for improving the energy efficiency of all other industries, through materials and manufacturing investments. As the DoE's interface to the National Network for Manufacturing Innovation (NNMI) program, AMO provides the DoE funding contribution to the program. The AMO's impact on this report has been primarily through this role.

The National Network for Manufacturing Innovation (NNMI) is a presidential initiative to create a network of hubs focused on transitioning advanced manufacturing technologies to commercial industry, thereby fostering innovation and creating jobs. These hubs provide a physical location to enhance industry-academia-government scientific collaboration with the intent of reducing the time between conceptualization and market availability. The hubs focus on material and manufacturing process

development, and are driven by the participating members and their areas of interest. The Department of Commerce National Institute of Standards and Technology (NIST) houses the NNMI National Program Office. These hubs are somewhat loosely modeled after Germany's Fraunhofer Institutes, and since being established, the number of planned hubs has grown from 8 to 45.

To date, four hubs have been created and the proposals for the fifth hub are under evaluation (Table 4). All hubs must be led by a not-for-profit organization, provide 50% cost share match, and are expected to become self-sufficient in 5 years. So far, all institutes are consortia with cost share being a combination of cash consortia fees, labor, equipment / software, and facilities. The DoD hubs have been coordinated through the DoD ManTech program.

In order for the DoD to maximize the benefit from these hubs, it is imperative that the Defense Primes (OEMs) and their supply chains participate; this will require cost share that cannot come from government sources. Further, Army PM / PEO participation is also necessary, as well as RDECOM participation to ensure that the voice of the Army is reflected in all the hubs so that the technology solutions meet Army needs. It is recommended that individuals from RDECs be assigned to specific NNMI hubs based on their inherent product interest. This would be the responsibility of the BoD and cross organizational research group proposed by the LCVSTC. These individuals would be responsible for soliciting input from the other RDECOM laboratories as well as providing information regarding projects, proposal processes, and other NNMI developments to the other RDECOM laboratories.

It is also recommended that the PEOs assign specific individuals to each of the NNMI hubs to provide the "voice of the customer." These individuals would have the responsibility of coordinating with each other as well as involving specific PM organizations into specific NNMI projects. Having the customers of the defense industrial base (DIB) involved in the hubs would create a large incentive for defense OEM participation. Further, Army involvement with the hubs would encourage them to reach out to the DIB to educate them on the type of cost share that would be allowed, and demonstrate that the NNMI can provide a business value to the industrial participant. The government representatives must encourage the hubs to focus not only on the large volume commercial producers, but also on the low-volume niche producers, many of which are members of the DIB.

Table 4. National Network for Manufacturing Innovation Hubs (NNMI).

Hub Name	Specialty	Gov't Lead	Est.	Location	Funding (Gov't + Cost Share)
America Makes: National Additive Manufacturing Innovation Institute	Additive Manufacturing	AFRL	2012	Youngstown, OH	$30M+$40M
Next Generation Power Electronics Manufacturing Innovation Institute (NGPEMII)	Affordable wide band gap semiconductor technologies	AMO	2014	Raleigh, NC	$70M+$70M
American Lightweight Modern Metals Innovation Institute (ALMMII)	Accelerate scale-up & application of lightweight alloys	ONR	2014	Detroit, MI	$70M+$70M
Digital Manufacturing and Design Innovation Institute (DMDII)	Digital design and interoperability across supply chain	ARDEC	2014	Chicago, IL	$70M+$70M
Clean Energy Manufacturing Innovation Institute for Composites Materials and Structures	Fiber Reinforced Resin Composite Technologies	AMO	2015	TBD	$70M+$70M

Lightweight Vehicle Approach

As mentioned in previous reports and reinforced at the workshop, the military does not have a modern light-weighting process, and developing one is a crucial responsibility of the BoD proposed by the LCVSTC team. Such a process must:

1. Maintain weight as the primary focus and not trade weight for performance
2. Ensure a vehicle systems perspective and not a sub-system perspective.
3. Use or develop operational metrics to determine the relative benefit of weight savings on operational performance of the vehicle (e.g., transportability/ton, fuel consumption/ton, fording/ton, reliability/ton).
4. Integrate material, manufacturing, and design models using Integrated Computational Materials Engineering (ICME) techniques (or similar).
5. Adopt weight optimization analysis software tools.
6. Have a deep understanding of the actual load, stresses, and other physical requirements of the vehicle subsystems over time.

Each of these will be described in turn. The specific implications of each recommendation may differ by sub-system and will also be elaborated upon in subsequent sections. There are other process barriers to light-weighting that will be discussed later in the report, but are generally beyond the scope of the LVCSTC.

Weight as a Primary Focus

Currently weight is a tradable system metric; a metric which is easily traded away to satisfy other metrics such as payload, performance, or price. As long as weight is traded for performance, no weight reduction technologies can be developed. Only in a weight reduction program where weight is paramount, can weight reduction technologies be developed.

A Vehicle Systems Perspective

Weight has a cyclic effect at the systems level. As additional capability (e.g., survivability) is added that significantly increases weight (e.g., additional armor), then engine performance must also increase to maintain mobility, which adds more weight. Heavier structures may then be needed to support the additional loads, and heavier suspension systems are needed to support the increased combined weight. This negative spiral also acts in reverse as a positive spiral for weight reduction.

Another aspect is space and size reduction. Reducing under armor volume through efficient packaging allows a reduction in the total amount of armor required; since armor is so heavy, this allows significant weight savings. However, reduction in the size of individual components or systems may not have any vehicle space reduction impact. Only when a critical "mass" of size reduction is achieved from several subsystems might an overall vehicle size reduction be achieved.

These sub-system weight and size interactions must be understood and taken into account to determine the total system weight impact from light-weighting technologies.

Operational Metrics by Weight

In order to understand the impact of vehicle weight and thereby justify the relative cost benefits of any technology, it is necessary to understand the operational effectiveness or cost on a per pound, or per ton level. For example, if weight affects transportability, then it is important to quantify by how much. Unfortunately, the maximum loading weight of the transport vehicle is too gross a number to serve as an effective metric by which to justify individual sub-system weight reduction benefits. A better metric might be cost associated with moving every ton or pound of a vehicle 1000 miles: $/ (1000 mile tons). For a given distance, the cost associated with each additional ton of vehicle weight could be computed. Additional operational metrics could justify weight savings by understanding the weight impact on fuel consumption (gal of fuel/ton) or reliability (MTTF/ton) of the vehicle.

This will enable the next step of weight reduction metric: $/lb of weight saved. This is a common metric used in commercial vehicle light-weighting to evaluate the cost benefit of competing light-weighting technologies. This has a strong implication on how weight savings is viewed, since the metric is not based on total weight saved, but rather on the cost of investment. This metric level-sets all light-weighting technologies based not on their total weight impact, but on their relative cost of weight reduction.

Integrated Computational Materials Engineering (ICME)

ICME is a process; it is not a single technology. Conceptually it integrates component performance simulation models, manufacturing process simulation models, and material response simulation models (see Table 5). These models are all developed for different purposes using different software. ICME is a method by which the specific models can talk to each other for design and manufacturing process optimization. Its major benefit is to accelerate the adoption of new materials to new applications.

Table 5. Integrated Computation Materials Engineering (ICME) integrates materials, manufacturing, and system performance models.

Subsystem	Material Models	Manufacturing Models	System Models
Armor & Structure	X ⟷	X ⟷	X
Automotive/Mobility	X ⟷	X ⟷	X
Armament	X ⟷	X ⟷	X
Electronics/Sensors/Other	X ⟷	X ⟷	X

This means that ICME is specific to a given product and manufacturing process. That is, models that are developed for a particular product, manufacturing process, and associated material cannot be used on a different component, manufacturing process, or material. The modeling tools are general, but the specific models developed within the software (or using the software) are application-specific. ICME is

the process by which these specific models can be integrated to understand the implications and reduce the risk of introducing a new material for a new product through an untried manufacturing process.

It is also very broad and requires sufficient scientific basis to be able to build the respective models. ICME need not be practiced across all model types and all components. Typically it is practiced where it makes sense. Thus, each of the sub-systems has a different ICME focus (see specific sub-system design recommendations below). For example, there is a need to better understand the material failure mechanisms of armor systems. Thus, basic research to build better material models for a particular material-threat combination will be needed before a complete ICME process for an armor system can be developed.

This is also an area where leveraging the NNMI hubs would be most valuable. For example the Lightweight Metals hub (ALMMII) is developing ICME-based products as one of its core missions.

Weight Optimization Analysis Software

In addition to ICME, which integrates models to better understand material impacts on manufacturing and system performance, additional tools now exist to optimize part geometry (topology) based on weight. Topology optimization software takes loads as an input and morphs an existing part shape by adding or removing material until a minimal weight shape is produced that meets all loading requirements. It is possible to place manufacturing constraints on the design to ensure the optimized shape is manufacturable. When such constraints are not placed on the design, many designs take on an "organic" shape, reminiscent of bio-inspired or biomimetic designs; recent advances in manufacturing processes (e.g., additive manufacturing) may now allow such complicated designs to be produced.

Given that these tools did not exist when most of our military systems were designed, it was estimated by one of the workshop attendees that many of the metallic components may over-engineered by 15% or more.

Understanding Physical Requirements

Any design process requires establishing loading requirements. The issue is that for specific vehicles that are designed to encounter particular events, those loading requirements may not be well-known or standardized. Specific examples that are well known are particular ballistic events, gun firing, train car impact, and turret lift. It is believed by the design community that all particular loading events might be foreseeable and have been applied on various vehicles, but that this application does not occur consistently, is not based on actual data describing what vehicles experience, and may not include time domain information to evaluate harmonics and fatigue. The greater the knowledge of the actual physical conditions the vehicle experiences, the less over-engineered (and therefore heavy) the vehicle will be.

Many automotive companies get their information by analyzing built-in sensor data (e.g., anti-lock braking sensors, acceleration data, and suspension data), as well as warranty data and failure analysis. The companies have sophisticated data-analysis methods for using this information to better understand how their vehicles are being used and improve their future vehicles.

Materials Development Efforts – by Workshop Sub-group

Armor & Structure Working Group Summary and Findings

Summary

The Armor & Structure Working Group identified several research thrusts and targeted S&T investments which are expected to have the highest impact on reducing system weight in the structural and armor components of ground vehicles. These components currently account for over 50% of the total vehicle weight. Overall the assessment was focused on near-, mid-, and far-term development of advanced materials, as well as potential exotic materials further out on the horizon, advanced manufacturing technologies, modeling and simulation (M&S) tools to provide disruptive capability in materials development, and design optimization approaches to light weighting. The primary finding is that an Integrated Computational Materials Engineering (ICME) approach to Ballistic Materials by design is needed to advance high-performance ballistic and structural materials. This approach includes developing a long-term moderate-risk strategy for ICME, and implementing low-risk approach to apply existing ICME concepts to ballistic materials and structural design in the short term.

The group recommends the following areas for Army investment:

1. Invest near-term in programs focused on ICME for ballistic materials.
    - These programs will enable the Army to engineer materials for Armor & Structure with the gained knowledge of how the material failures occur.
    - This knowledge gained regarding failure under ballistic and blast loads will enable the Army to focus on fewer, higher-impact material research programs with a higher potential for transition.

2. Invest near-term in understanding the commercial design tools that are available and developing a design optimization approach for weight reduction applicable to Army systems.
    - Design optimization will enable component designs to be tailored to the advanced materials derived through the ICME process.
    - Packaging envelopes could be reduced and thus so could weight and cost.

3. Maintain current material research S&T investments in the near term, leverage work in the ICME and focus on design optimization arenas to define future S&T investments.
    - Metals – Next-generation alloys (Ultra-High Strength Steels, Aluminum, Titanium, and Magnesium), Nano-crystalline alloys, dual-hard materials,
    - Ceramics – Next-generation ceramics for opaque and transparent armor, ductile deformation mechanisms,
    - Composites – including carbon nano-tubes and graphene,
    - Polymers.

4. Increase investment in joining and advanced manufacturing technologies for emerging materials through manufacturing technologies (ManTech) and other manufacturing avenues where external (industry, OGA, academia) investments fall short.
    - Require high-potential emerging materials to have supporting joining and manufacturing programs.
    - These programs will be driven by the materials developed through the ICME and material research programs.
    - To enable earliest material transition, the manufacturing programs must be executed early on and in parallel to the material development program that they support.

5. Become an active voice in the NNMI hubs and provide the Army needs to the consortia as derived from ICME and design optimization programs.

Investment Recommendation Lines of Effort

Based on the above areas of recommended investment, Figure 7 illustrates the proposed timeframe and coordination within the Armor & Structure line of effort. Overall the chart highlights that current S&T investments will lead to an estimated 24% weight reduction, while the additional S&T investments highlighted could increase that reduction as high as 38%. Future S&T investments would be dependent on the decisions made by the BoD. The Army must change the way we invest in research and approach weight reduction, and the critical efforts that must be executed for success are highlighted in blue. These include forming programs to understand the loads that our materials must withstand, so that we can develop a concurrent design optimization approach for the specific needs of the Army. Additionally, a BoD must be formed so that it can engage each NNMI hub to leverage the work being executed under those initiatives and align some of their goals with Army needs. The dashed lines encompass a set of studies that must be conducted between operational energy models, vehicle concept models, and force-on-force models to develop cost and performance metrics that will inform material S&T investments and vehicle design.

The next two lines of programs represent the current Materials in Extreme Dynamic Environments (MEDE) program and additional ICME work. The team recommends further investment in these areas so that we can understand why and how materials fail during ballistic events, and then roll that information into material and armor package design. This set of programs will drive how the Army invests in material research for Armor & Structure, by enabling material science experts to predict how new materials should be tailored for optimal defeat of a given threat. With this understanding will also come the ability to invest heavily in a sub-set of materials that will have a higher probability of being integrated into a final armor solution. Since the Army does not have this capability at present, and given that the current material science portfolio covers the most probable material candidates for application against future threats, we recommend that these S&T investments continue until the design optimization and ICME programs reach an initial state of maturity. The Army would then have additional information to redefine its material S&T investments and divest in areas with a lower probability of transition, while increasing S&T investments in more favorable materials. Finally, the

materials selected for investment will then drive advanced manufacturing and joining research, along with demonstrator programs, that should be conducted in parallel with the material research.

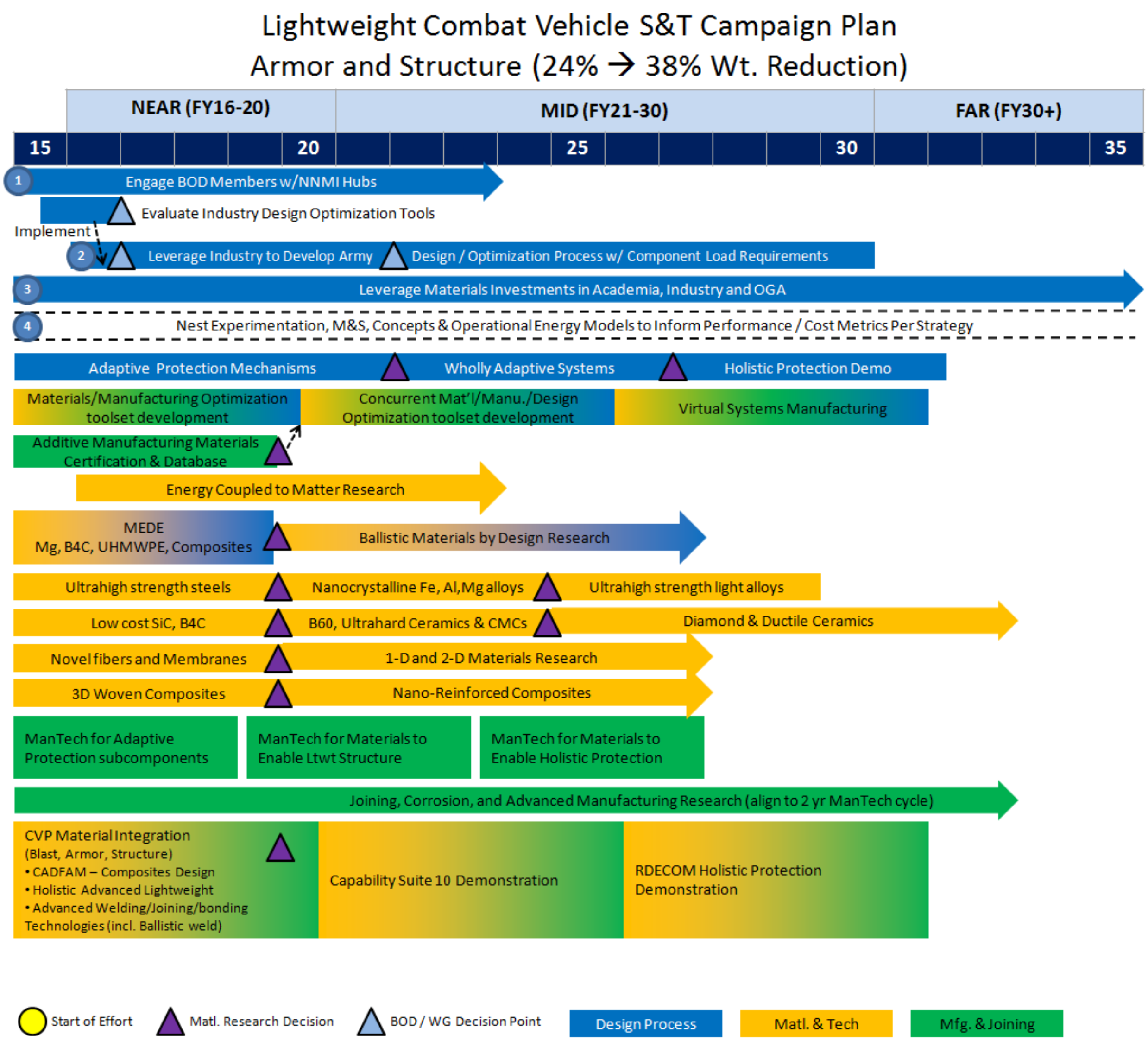

Figure 7. Lightweight Combat Vehicle S&T Campaign Plan - Armor & Structure.

Current Army Programs

Accounting for over 50% of the vehicle weight in a combat system, Armor & Structure represents the largest subsystem of a combat vehicle. Table 6 breaks out the major components of the sub-system which also highlights the number of armor packages on the vehicles. While each component could be assessed in terms of weight reduction individually, the hull and all of the armor packages work together. From a design standpoint, weight reduction to one component -- if undertaken without considering performance of the complete package -- could hinder the entire system and require weight growth elsewhere. Total sub-system weight, materials, and performance were all taken into account when considering future material and technology insertions for weight reduction.

Table 6. Abrams M1A2SEP and Bradley M2A3 weights by major vehicle component.

		Abrams M1A2 SEP		Bradley M2A3	
Hull			**48,677**		**37,551**
	Structure / Armor	28,759		8,580	
	Add-on Underbody	4,800		1,997	
	Ballistic Bolt-on Armor			8,470	
	Add-On CE Armor	8,920		12,053	
	Appendages	6,198		6,451	
Turret			**32,517**		**4,561**
	Structure / Armor	30,665		1,640	
	Ballistic Bolt-on Armor			1,730	
	Add-CE Armor	1,340		386	
	Appendages	512		450	
	Turret Associated Components			355	
Gross Subsystem Weight (lb)			**81,194**		**42,111**
	(Tons)		**40.6**		**21.1**

To identify potential gaps in the Army's current S&T portfolio for Armor & Structure, the existing Army programs that support weight reduction, both funded and unfunded were reviewed (Figure 8). Since Armor & Structure is typically the focus of Army programs with respect to increased capabilities and weight reduction, it is not surprising that only one of the programs in Figure 8 is unfunded. While there are no programs slated to go past 2020, Armor & Structure has a well-rounded portfolio that encompasses design, materials and manufacturing. Based on the Army's existing portfolio, gaps and program recommendations were identified with the goal of pushing the state of the possible by 2030, rather than filling a specific and immediate technical void.

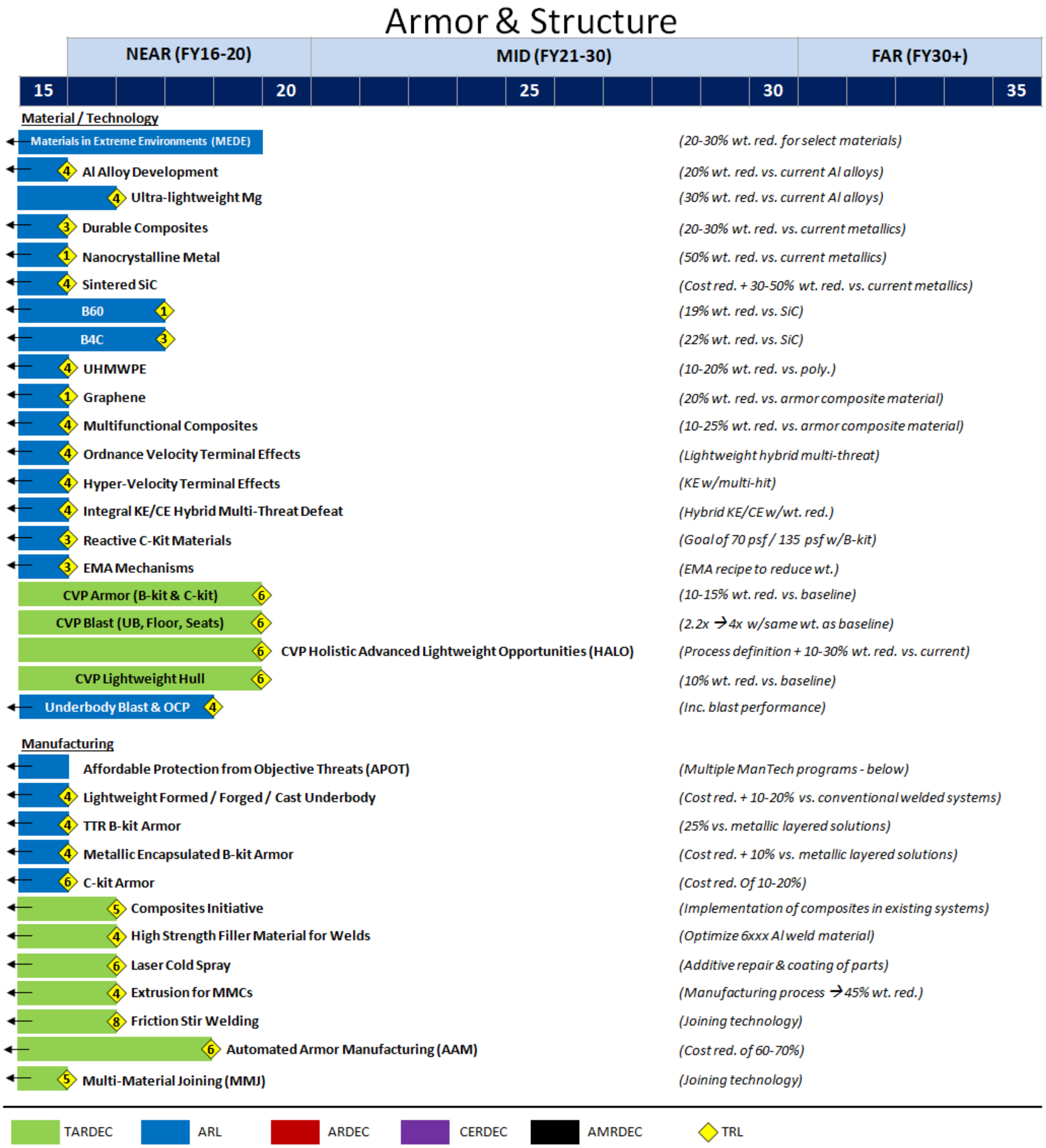

Figure 8. Armor & Structure materials, technology & manufacturing Army investments.

Design Gaps and Recommendations

After reviewing the current Army programs, one of the largest gaps that was highlighted was in design optimization. Currently the Army is only looking at design of materials as part of the MEDE program; however, this process must be expanded to all materials and to the optimization of armor & structure components. Additionally, without a material design approach in place, the Army is limited in its ability to tailor material solutions and S&T investments in the area of Armor & Structure. Therefore, a wider

net of material research must be cast to ensure that we investigate all potentially viable solutions for the next generation, rather than engineering singular material solutions to meet specific criteria. To close this gap, two solutions in the design arena were identified and are discussed below.

Integrated Computational Materials Engineering (ICME)

The team determined that there is an insufficient understanding of the processing, property, and dynamic response relationships needed to drive ICME-based material development for ballistic materials. Without understanding the material responses under the extreme loads of Army usage, it is impossible to engineer materials specifically to withstand these loads. While the MEDE program begins to examine the basic technical information required for using the ICME approach in Armor & Structure, we still need to establish a program of fundamental materials science for ballistic materials. Such a program would involve research efforts to identify how materials physically fail during a ballistic event. This will enable the Army S&T community to gain a better understanding of the underlying material and armor mechanisms, and to develop and exploit modeling and simulation tools for designing future lightweight materials that will withstand extreme dynamic events.

Optimization of Structure, Materials & Design

Advances in optimization of structure and materials focuses on developing a modular or new form factor other than the “boxy” form factor that is common to all combat vehicles. The working group discussed whether this is due to this form factor being (a) an optimal configuration using existing state-of-the-art material and manufacturing technologies, or (b) a carry-over form of what was historically done due to then-existing material limitations (e.g., being constrained to plate product forms). If simply a historical carry-over, the design optimization tools could enable radically new vehicle designs that are lighter and still meet all performance requirements. New engineering design tools are being developed to incorporate not only design optimization but also to include materials-by-design and design-for-manufacturing methodologies. The use of these tools is expected to result in efficient structures and uses of materials such as laminated, functionally-graded structures, or variable cross-section geometries where the most efficient and optimal configuration puts material exactly where needed without excess mass. Other multi-disciplinary optimization methodologies are emerging that will optimize not only the design but the manufacturing process to achieve the design. This provides a design-for-manufacturing capability while maintaining an optimal configuration.

Thus, from a design standpoint we recommend that the Army:

1. Invest near-term in programs focused on ICME for ballistic materials.
    - These programs will enable the Army to engineer materials for Armor & Structure with the gained knowledge of how the material failures occur.
    - This gained knowledge of failure under ballistic and blast loads will enable the Army to focus on fewer, higher-impact material research programs with a higher potential for transition.

2. Invest near-term in understanding the commercial design tools that are available and developing a design optimization approach for weight reduction applicable to Army systems.
    - Design optimization will enable component designs to be tailored to the advanced materials derived through the ICME process.
    - Packaging envelopes could be reduced and thus so could weight and cost.

Materials Gaps and Recommendations

Material development is a large arena within the Armor & Structure community. Lighter, more mass-efficient materials, including advanced alloys and emerging materials, are constantly being researched for incorporation into future solutions. Given the wide range of material programs within the Army (Figure 8), the assessment of this portion of the Army's portfolio included existing programs covering a range of emerging materials inside and outside the DoD for Armor & Structure. This study revealed that the Army's current investments in material research for Armor & Structure encompass the applicable materials that are available, both currently and on the horizon. While other materials do show promise for far future applications, additional development (or an ICME approach for ballistic materials) is needed to discover whether or not they will be applicable for combat systems. Regardless, in the 2030 timeframe the below general categories of materials are highlighted due to their potential for being more mass-efficient, and their ability to be integrated into package solutions.

Metals

Metals have the highest level of utilization within the material classes, and will maintain this position for the foreseeable future. In the metals space, several properties are of interest to all material systems: strength, toughness, ductility, stiffness, hardness, and affordability. Steel's combination of performance and cost has driven it to be the standard for Armor & Structure for fighting vehicles. Next-generation ultra-high-strength steels (UHSS) are needed to drive performance and weight reduction. Dual hard steel was discussed as a material of interest due to its mass efficiency and cost; and, given the advances in UHSS, this technology warrants future investment.

For the long term, nano-crystalline metals show promise due to their potential to bring a disruptive jump in mechanical properties. Whether using Iron (Fe) or Aluminum (Al), this technology is of interest for future investment to improve production scalability.

Aluminum is the second most widely-used material in the Army's fleet. Next-generation Aluminum alloys are needed to increase the performance and/or reduce the weight. New alloys in the 2XXX, 7XXX, and more exotic alloys such as Aluminum-Lithium or Aluminum-Rare Earth series, are of particular interest. Investment in welding technologies is a priority to enable more widespread use of these Aluminum alloys.

Magnesium (Mg) is the lightest (least dense) of all the structural metals. Investments in the MEDE Collaborative Research Alliance (CRA) are leading the development of new insights and understanding of Mg behavior. If it proves possible to develop Mg alloys of high enough strength, offsetting the usage of Al, 30% weight reductions are possible. We will consider investments in promising Mg alloys that reach

strength levels required and support weight reduction are showing promise for attaining strength levels to achieve this goal, so this technology should be considered for reduction of weight in the structure.

Titanium (Ti) is rarely found in combat or tactical vehicles to date. While there have been several studies and concept vehicles/structures made to demonstrate the benefits of Ti, its higher cost over conventional materials have prohibited its use. Research into ballistic weld development and additive manufacturing is needed to investigate whether these may impact the usage of Ti for Army applications.

Shape memory alloys are a potential multifunctional technology enabler of active structure developments warranting further research and potential development.

Al alloys have never been specifically developed for armor, due to the relatively small volume of production. Historically, the Army relied on industry (e.g., automotive and aerospace) to drive advanced Al alloy developments. Unfortunately, these industries typically focus on thin-gauge products compared to Army requirements for thick-gauge ballistic and structural materials. Therefore, developments of advanced alloys in thick sections will require Army investment.

Ceramics

A variety of opaque and transparent ceramics are potential enabling materials to drive weight reduction in vehicles. Next-generation ceramics with improved or disruptive properties will be more affordable when combined with advanced manufacturing processes. Next-generation and lower-cost silicon carbide (SiC), boron carbide (B_4C), and boron suboxide are potential near-term options. Cubic boron nitride is one of the hardest materials currently available and could serve as a mid-term option, but will require overcoming significant scaling and manufacturing process challenges. Longer-term ceramic candidates include diamond and flexible/ductile ceramics.

Composites

There are several ways to improve existing composites and advance the non-traditional composite materials. The development of high-performance composites is supported by next-generation fibers (such as glass, carbon, Ultra-High-Molecular-Weight Polyethylene (UHMWPE)) and the incorporation of nano-materials such as graphene, carbon nanotubes (CNT), and boron nitride nanotubes (BNNT). CNT-reinforced composites are projected to be available within a 10-year timeframe but require investments in large-scale synthesis techniques (e.g., chemical vapor deposition) to achieve the required purity levels. Carbon-based fullerene reinforced composites possess promising properties, but are currently very expensive and early in the development phase. Another near- to mid-term focus area should include ceramic matrix composites (CMC). The team identified Titanium-based composites (TiB2 + TiN or TiB2 + TiC) as a potential CMC in which the microstructure can be tailored and made to support scalability, formability, and affordability. Other composite materials identified include metal matrix composites (MMC) currently at TRL 6, bi/tri-continuous composites which needs continued development, and fiber metal laminates (FML) currently available at TRL 6.

Polymers

Next-generation adhesives will complement research in other materials by enabling joining technology of composites and dissimilar materials. Advanced thermoplastics have potential structural applications ranging from existing materials at TRL 6 (next-generation UHMWPE), to longer term developments. The development of advanced polymers for applications outside of the Armor & Structure area, such as capacitors and energy storage, could also enhance the reduction of structural/armor weight and volume.

Given that these general areas of materials are already within the current Army S&T investments, it is recommended that the Army:

1. Maintain current material research S&T investments in the near term and leverage work in the ICME and design optimization arenas to define future investments.

Manufacturing Gaps and Recommendations

The Army is currently investing in a number of ManTech programs to support the material development in Armor and Structure. While these programs cover large-scale manufacturing, joining, and processing of advanced materials, the manufacturing programs must continue to evolve as additional materials are developed. Currently, emerging materials appear to be outpacing the manufacturing research that supports them. Without means to manufacture or join the emerging materials, they will never transition to a combat vehicle. In order to close this gap, two key areas within manufacturing are discussed below.

Joining Technologies

A key gap is in joining technologies. This area includes welding (particularly of dissimilar materials), and adhesive joining. Near-term research is needed to advance joining technologies to avoid parasitic weight gain due to extra hardware required for attachment of armor and structures. Focus should be on multi-material joining, field-portable friction stir welding, and adhesive and composite joining technologies. Joining of dissimilar materials will enable hybridized structures in which materials could be used specifically where their properties are needed (i.e., functionally-graded structures). A common observation, particularly from the vehicle integration community, was that advanced materials which could enable significant weight savings are often not viable alternatives due to joining and sustainment challenges.

Advanced Manufacturing

The Army also needs advanced manufacturing technologies to complement the design methodologies. Design-for-manufacturing disciplines are necessary to ensure that the technologies being developed are manufacturable and affordable. Affordability must be considered, as it is one of the major reasons for acquisition program termination. Advanced manufacturing, particularly layer-by-layer, and additive

manufacturing processes, hold great promise for generating new structures and design spaces that may have been prohibitive or impossible under traditional manufacturing approaches.

The manufacturing recommendations for the Army must be directly tied into the design and material programs, as each will direct the other. For manufacturing, the following items are recommended for the Army to pursue:

1. Increase investment in joining and advanced manufacturing technologies for emerging materials through ManTech and other manufacturing avenues, where external (industry, OGA, academia) investments fall short.
    - This path requires high-potential emerging materials to have supporting joining and manufacturing programs.
    - These programs will be driven by the materials developed through the ICME and material research programs.
    - To enable earliest material transition, the manufacturing programs must be executed early on and in parallel to the material development program that they support.

2. Become an active voice in the NNMI hubs and provide the Army needs to the consortia as derived from ICME and design optimization programs.

Automotive / Mobility Working Group Summary and Findings

Summary

Multiple S&T investments in this area will reduce the number and weight of automotive/mobility components of ground vehicles, and thus, overall system weight. Most of the identified components have the potential for large weight savings through simple design optimization. Unfortunately, the Army is significantly behind industry in defining component loads and applying design optimization tools. Future efforts require the development of metrics, design optimization processes, and advanced manufacturing technologies. Many of these findings are similar to those in the Armor & Structure section; however, unlike Armor & Structure, the Automotive/Mobility area has the advantage of leveraging many of the automotive/mobility components, design processes and materials from the automotive industry.

The group recommends that the Army take the following actions:

1. Investigate operational energy models and metrics to develop cost metrics for lightweight materials and technologies.
    - This enables the quantification of metrics that will drive R&D S&T investments towards solutions that will cost-effectively reduce vehicle weight.

2. Invest in component design and optimization tools, and develop a process for lightweight design in the near term.
    - We need to understand our loads and optimize existing components. Weight reductions of 10-20% in the automotive industry are typical for any component considered (e.g., Abrams road arm is a solid cross-section and could achieve approximately 50% in weight savings via finite element analysis [FEA]).
    - Geometry and material (both informed by manufacturing processes) are intimately connected and cannot be separated.
    - Significant weight savings are possible with current materials, and if more advanced (and expensive) materials and manufacturing were used, these could potentially be cost-neutral when cost assessments are made at the vehicle level instead at the sub-component level.

3. Enable technology insertion on currently-fielded platforms before reacting to a requirement.
    - Technology and materials can be proved out on systems in the field instead of waiting for major vehicle development efforts. This reduces risk to the new systems and accelerates development.

4. In conjunction with the design optimization programs, the Army will leverage the materials being developed within the automotive industry and DoE VTO in the near term.
    - Assess how much weight reduction these materials will enable.
    - Use design optimization to guide the development of military-specific alloys.

- Investigate operational energy models and metrics to develop cost metrics for lightweight materials and technologies.

5. Ensure that advanced technologies such as Hydropneumatic Suspension Unit (HSUs), cooling systems, and power plant designs incorporate weight reduction through material optimization at the component level.
    - Also include alternative approaches such as engine downsizing and advancements in waste heat recovery.

6. Invest in far term automotive / mobility alternatives such as fuel cells and advanced suspension designs.
    - Research and development of an advanced propulsion system and/or system layout, that is viable for the Army.
    - Currently the 30-35 ton weight goal must be a tracked, rather than wheeled, system. What would it take to enable a wheeled, hybrid, or alternative approach with equivalent mobility? (Initial tests indicate this is possible - Republic of Korea Multiple Launch Rocket System and US Marine Corps Marine Personnel Carrier)

7. Increase investment in joining and advanced manufacturing technologies for emerging materials through ManTech and other manufacturing avenues where external (industry, OGA, academia) investments fall short.
    - Require high-potential emerging materials to have supporting joining and manufacturing programs.
    - These programs will be driven by the materials developed by the automotive industry and Army R&D efforts, and design optimization assessments.
    - To enable earliest material transition, the manufacturing programs must be executed early on and in parallel to the material development programs that they support.
    - Ablation casting is an emerging example that enables a quick quench and improved material properties.

8. The Army needs to engage the national manufacturing centers to ensure that the manufacturing needs of the Army are addressed.
    - Current manufacturing base in several materials of interest are not able to participate fully in export control compliance processes.
    - Army has specific material gauge needs that are not addressed by any other industry.

Investment Recommendation Lines of Effort

Based on the above areas of recommended investment, Figure 9 illustrates the proposed timeframe and coordination within the Automotive/Mobility line of effort. Overall the chart highlights that current S&T investments will lead to an estimated 29% weight reduction, while the additional S&T investments highlighted could increase that reduction as high as 54%. Future S&T investments would be dependent

on the decisions made by the BoD. The critical efforts that need to be executed for the Army to change the way we invest in research and approach weight reduction are highlighted in "blue." Formation of a BoD or similar functioning group early in FY15 is necessary to engage each program slated for the next vehicle PoR and ensure that weight reduction is a key component of their design and technology maturation plan. Additionally, this BoD will engage the NNMI hubs to leverage their work and help align some of their goals with Army needs.

In addition to this, the Army must put forth the effort in the near term to define the specific design loads that our materials and components are exposed to during operation (e.g., automotive shock and vibration, anti-personnel mines, etc.), and to develop a concurrent design optimization approach for Army specific needs. The dashed lines encompass a set of studies that need to be conducted between operational energy models, vehicle concept models, and force-on-force models to develop cost and performance metrics that inform material S&T investments and vehicle design. The final blue investment is a brief study that will assess whether or not early technology insertion using Engineering Change Programs (ECPs) would benefit the Army's development or transition of technology. While this works for the automotive industry, their design cycle time and competitive market enable the early technology insertion process to be beneficial, whereas for the Army environment it may be less so.

The orange programs represent material and technology investments. In the near term, the Army should stay informed on the materials that the automotive industry is developing, and as part of the design optimization, execute a program to leverage the materials deemed most appropriate to military components. Additional material and technology program investments, spanning the near- to far-term, should research advanced suspension, propulsion and cooling technologies including HSUs, fuel cells, waste heat recovery, and so on. Concept studies are necessary to understand potential trade-offs of wheeled versus tracked configurations associated with vehicles heavier than 30 tons. Finally, the materials selected for investment will then drive advanced manufacturing and joining research that should be conducted in parallel with the material research.

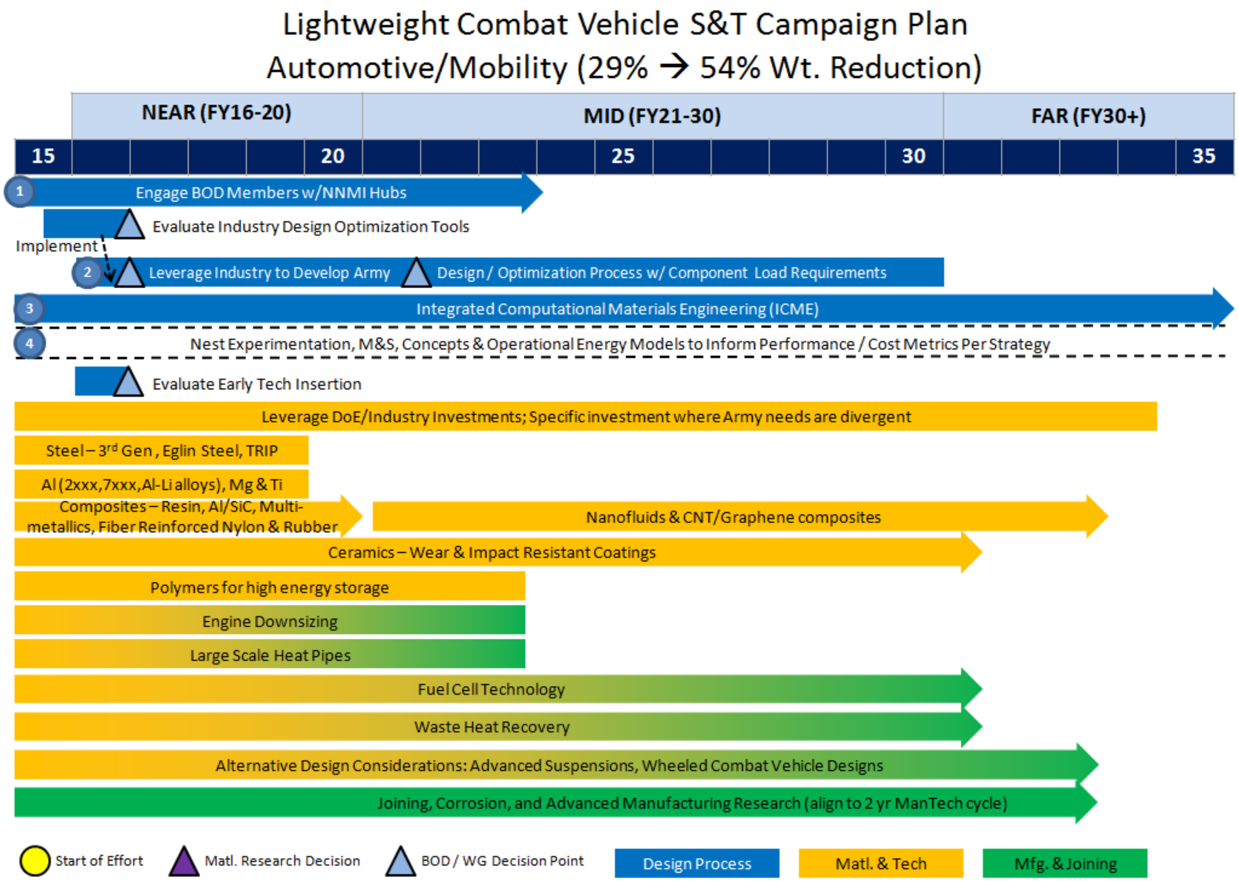

Figure 9. Lightweight Combat Vehicle S&T Campaign Plan - Automotive/Mobility.

Current Army Programs

At nearly 30% of the vehicle weight, the Automotive / Mobility components represent the second largest weight allocation for a combat vehicle. Table 7 illustrates some of the primary component weights of the Automotive / Mobility system on an M1A2 SEP. Compared to standard automobile components, the suspension components on a combat vehicle are disproportionately heavier. These components are considered to be "over-designed" – that is, they are generally heavier than they need to be to support the required loads. However, a portion of this overdesign is derived from the survivability requirements of the vehicle system, and moreover, military vehicles must operate in conditions that would be considered extremely harsh in the passenger automotive market. Thus, when attempting to reduce the weight of these components, all of the operational loads must be considered.

Table 7. Subsystem components and weights.

		Abrams M1A2 SEP		Bradley M2A3	
Suspension			**24,025**		**12,273**
	Spring & Damping	3,934		1245	
	Roadwheels & Roadarms	7,034		3923	
	Track Drive System	893		330	
	Track Return Rollers	231		274	
	Track (156 Track Shoes)	10,639		5870	
	Track Tension System	1,101		591	
	Miscellaneous	193		40	
Power Plant & Drive Train			**11,038**		**6,870**
	Power Plant	2,715		2,780	
	Drivetrain	4,695		2,215	
	Final Drives	1,989		850	
	Induction/Exhaust System	906		255	
	Cooling System	733		770	
Auxillary Automotive			**2,346**		**764**
	Chassis Hydraulics	399			
	Crew Accomodations	177		270	
	Fuel System	817		494	
	Automotive Control	348			
	Environmental Control	546			
	Special Purpose Accomodatio	59			
Fuel			**3,048**		**1,325**
Gross Subsystem Weight (lb)			**40,457**		**21,232**
	(Tons)		**20.2**		**10.6**

Figure 10 is a review of existing Army programs in Automotive / Mobility that support weight reduction. A significant portion of the component design programs are unfunded (light green), and there are no programs beyond 2020. Most of the funded programs are focused on secondary weight reductions through technology advancements such as the Advanced Combat Engine, and are not necessarily investigating advanced materials. Conversely, most unfunded programs are focused on design using advanced materials with technology improvements. These unfunded programs not only represent a general gap in the Automotive / Mobility S&T portfolio, but they also represent a significant weight reduction potential. Based on the existing programs within the Army's portfolio, the team highlighted additional gaps and made recommendations to drive weight out of the Automotive / Mobility components by 2030.

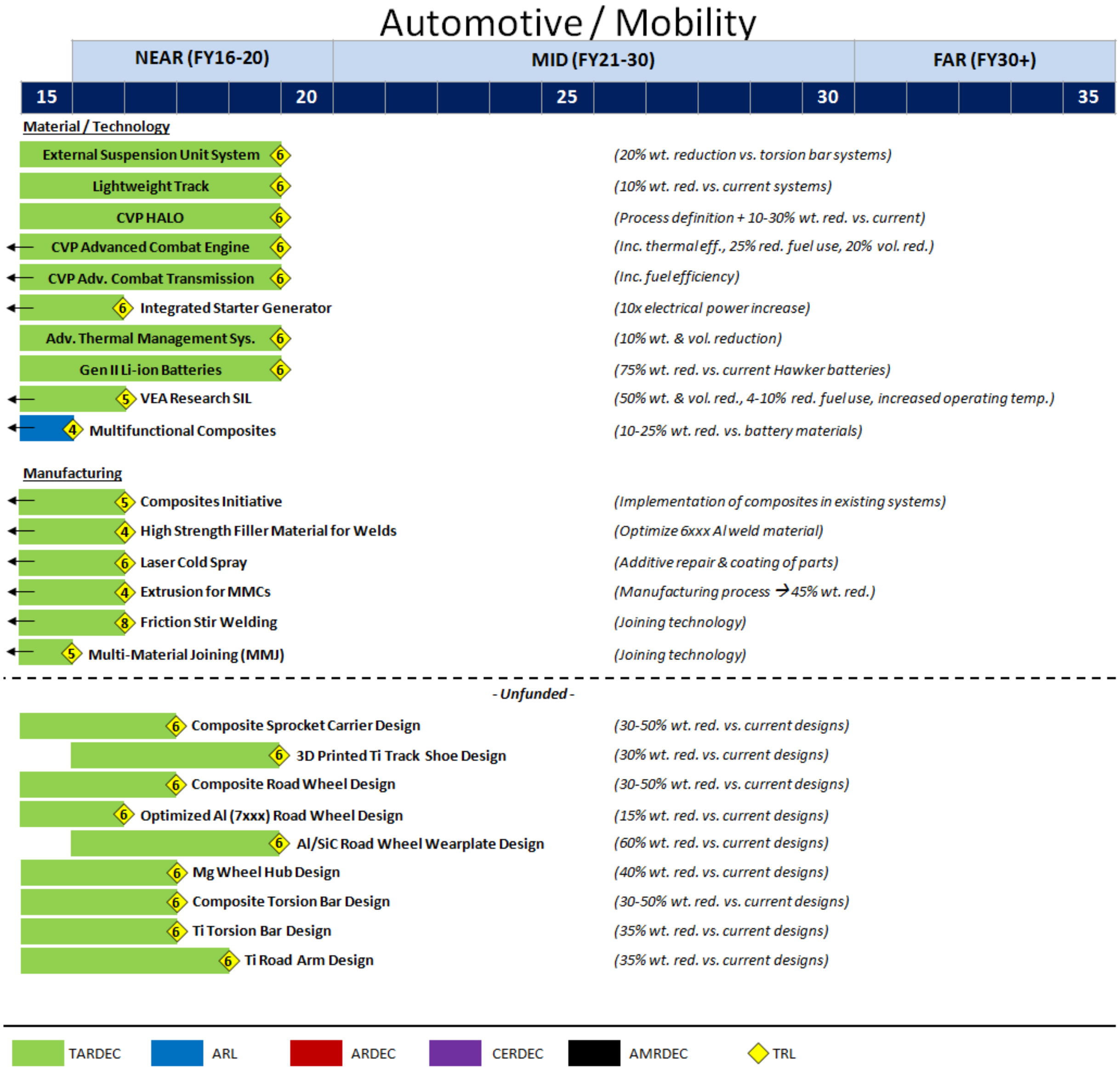

Figure 10. Automotive/Mobility materials, technology & manufacturing Army investments.

Design Gaps and Recommendations

Using weight as the key design parameter for combat Automotive / Mobility systems will be a paradigm shift from the standard way that the Army does business, which is to drive capability advancements. Weight has always been a concern for combat systems; this campaign will help ensure it becomes a key metric that impacts whether or not a vehicle program continues through the acquisition cycle to production. This shift aligns the Army more with commercial products where weight has always been a key metric. Unfortunately, the Army is "20-25 years behind industry"[19] in understanding the loads and requirements for each component design. Thus, most of the tools and software used in industry to take weight out of a component or subsystem today have not been leveraged by the Army or its OEMs. In

order to enable the weight reduction methods that are used in the automotive industry, and close this gap, several recommendations in the design process are discussed below.

Lightweight Metrics

The Army does not currently have metrics to measure and assess the "goodness" of weight reduction S&T investments, such as $/lb saved, which the automotive industry uses to drive acceptable weight reduction solutions. Additionally, there are no formal requirements to drive the weight down or to justify the investment in the materials or design methods to reduce weight. As an example, automotive projects typically do not go to production unless they are less than $6/lb saved. These metrics focus R&D into "acceptable" lanes and drive additional manufacturing and integration development.

Defining a metric such as this for the defense industry, particular to each platform, will define a lower bound for cost tolerance. An upper bound for cost tolerance could then be derived from the full lifecycle costs (including such things as fuel, maintenance, and transportation costs) over a tolerable payback period, e.g., 3 to 5 years. Operational Energy metrics can drive the material and technology investments by linking them to pay-offs in the field, such as number of convoys required and gallons of water used versus input metrics such as reliability, maintainability, fuel efficiency, and scenario definition. These cost metrics will define component designs, and weight savings from these components could allow other component weights to be decreased (i.e., secondary weight savings). These additional weight savings are usually between 25% and 70%.

To enable transition to production, the Army must consider the importance of these cost metrics in its technology development work. Without these tolerance-bound metrics, each feasible and lighter-weight solution is quickly abandoned or rejected due to a lack of funding or written requirement. As a result, identifying and transitioning weight reduction opportunities in military systems becomes a frustrating and cyclical experience for the technical community. The user community desires the weight reduction, yet the acquisition community has no way to justify the investment as being worthy of investment.

Design Optimization

As in the Armor & Structure Working Group, the Automotive / Mobility Working Group finds that the use of design optimization tools in developing Automotive / Mobility components is almost non-existent. We lack an understanding of the peak loads on each component, which change due to weight increases over the life of the vehicle, leading to overweight components. Components designed without having been optimized can typically realize 10-20% weight reductions through optimization techniques (that is, by removing material in non-critical locations), while using the same material. Additionally, advanced multi-material design approaches can be applied based on stress levels in the parts. Though they may be more expensive ounce for ounce, these advanced designs require a reduced amount of material versus a non-optimized part, with the result that weight reductions can be achieved with a minimal, or no, cost penalty.

Technology Insertion

While materials and technologies are developed in parallel with vehicle programs of record, many of them fail to be inserted onto a vehicle platform until a specific performance requirement pushes the insertion. This is contrary to how industry develops technology. Instead of waiting for a new vehicle platform that requires several new, previously unfielded materials or technologies, industry will incrementally incorporate these items into current platforms. This decreases the risk for the later fielded vehicles and accelerates the development of the technologies being inserted (i.e., Boeing's use of composites). Although ECPs for military systems offer this avenue, a requirement is still needed to incorporate a new technology. Ideally, if a new material or technology is promising, early insertion to a current vehicle is done prior to the identification of a specific requirement. In the Boeing example, composites were recognized as the path forward, so Boeing inserted composites into their designs before there was a business case to do so. Because of the risk reduction that this enabled, and the additional data gathered to drive the technology, composites now account for over 50% of the structure weight in their current designs. Automotive / Mobility components can follow this same philosophy. Advanced materials and designs can be integrated onto current systems now, which will reduce the risk to the next program of record and push the most promising technologies to the field faster.

Given these three topics focused on the design aspect, it is recommended that the Army:

1. Investigate operational energy models and metrics to develop cost metrics for lightweight materials and technologies.
    - Enable the quantification of metrics that will drive R&D investments toward solutions that will cost effectively reduce vehicle weight.

2. Invest in component design and optimization tools, and develop a process for lightweight design in the near term.
    - We need to understand our loads and optimize existing components. Weight reductions of 10-20% in the automotive industry are typical for any component considered (e.g., Abrams road arm is a solid cross-section and could achieve approximately 50% in weight savings via finite element analysis [FEA]).
    - Geometry and material (both informed by manufacturing processes) are intimately connected and cannot be separated.
    - Significant weight savings are possible with current materials, and if more advanced (and expensive) materials and manufacturing were used, these could potentially be cost-neutral when cost assessments are made at the vehicle level instead at the sub-component level.

3. Enable technology insertion on currently-fielded platforms before reacting to a requirement.
    - Technology and materials can be proved out on systems in the field instead of waiting for major vehicle development efforts. This reduces risk to the new systems and accelerates development.

Materials Gaps and Recommendations

Programs within the Automotive / Mobility area are primarily focused on technologies that offer increased capabilities. However, advancements in heat treatments and wear-resistant coatings are investigated to increase the lifetime of the components. Because of the large overlap with the automotive industry, most of the materials developed and used in the auto industry can be leveraged by the Army. These materials could offer additional weight savings to Automotive / Mobility components, with appropriate design optimization. Review of the current materials used within military systems is a logical path forward and will help focus future material solutions as the Army gets closer to the goal of 30- 35 ton combat vehicles in 2030.

Suspension

The suspension sub-system can benefit from additional materials, more specific design parameters and advanced technologies. The current materials used within the suspension system (Forged 2014-T6 and 4140/4340 Q&T) are the correct materials for most components. However, there are new materials that will become available within the next five years that could offer additional weight reduction over a simple design optimization. It is difficult to give an accurate estimated weight savings based on a material swap alone without a component re-design. Modern analysis and design methods iterate between design and material selection, often compounding the primary weight savings. Table 8 highlights the materials that are not being utilized by current combat vehicle suspension systems, but will be available for application in the next 2-5 years.

Table 8. Materials not currently utilized in combat vehicle suspensions, but available for application in next 2-5 Years.

Components	Materials
Springs & Damping	Ti, Resin Composite w/Metal Alloy, Al/SiC
Road wheels & Road arms	Gen III HSS, Eglin Steel, Resin Composite w/Metal Alloy,
Track Drive	Multi-metallics, Wear & Impact Resistant Weld-on Coatings, Al/SiC
Track Idler & Tension	Multi-metallics, Wear & Impact Resistant Weld-on Coatings, Al/SiC
Track	TRIP Steel, Gen III HSS, Aluminum, Titanium, Wear & Impact Resistant Weld-on Coatings, Al/SiC, Fiber Reinforced Nylon, Fiber Reinforced Rubber, Urethanes

In addition to the materials that could be utilized for the suspension system, the specific design changes that could be applied to these components are:

1. Redesign and change the hub, road arm, and spindle away from a solid forged design to hollow cross-sections.
2. Utilize a 2-piece wheel design to enable the optimal material to be applied for the required loads on different areas of the part.
3. Design re-buildable track shoes with either aluminum or steel.
    - Would minimize operational cost to enable more exotic materials to be used for weight savings by applying a specific material property at the specific point of need.
    - Embedded sensors to minimize crew checks.

- Hollow geometry cross-sections to enable the same performance parameters at a fraction of the weight.

Applying advanced technologies in the mid- and far-term can also reduce the weight of the suspension components through application and manufacturing. As an example, the track of a combat vehicle has a large amount of metal in the design to maintain tension. However, future S&T investments in band track systems for a 35-ton vehicle would enable a significant amount of weight to be removed from this component. The following technologies would enable longer-term solutions to be available in addition to materials:

4. Advanced suspension designs.
    - Utilize hydraulic suspension units to replace road arms and torsion bars.
    - Utilize an elastomer band track which could lead to secondary increased efficiencies.
    - Develop a wheeled layout vs. track for a 35-ton vehicle with equivalent mobility (Currently, 20- to 30-ton range). Initial tests indicate this is possible - Republic of Korea Multiple Launch Rocket System and US Marine Corps Marine Personnel Carrier.
    - Utilize solid composite (non-pneumatic) wheels (currently, 20-ton range).

Power Plant & Drivetrain

Military propulsion systems often sacrifice efficiency for more compact size, since the volume of the power plant and drivetrain drive the under-armor volume of the vehicle. Since the armor is the heaviest component on the vehicle, minimizing this package space is critical if weight reduction is being considered. Thus, we run lower-displacement engines at higher-speeds, knowing we are sacrificing efficiency for the purpose of power density (hp/in^3). Additionally, minimizing heat rejection is crucial because it drives the size of the cooling system.

The largest savings in efficiency and heat rejection minimization will be gained by utilizing thermodynamic combustion. Thermodynamic heating allows for the minimization of the cooling system, fan sizes, and openings in the armor for heat exchangers, and reduces power consumption while increasing survivability. Since the Army currently has Advanced Combat Engine and Transmission programs, the below table highlights additional items that can be investigated in the near to far terms (Table 9).

Table 9. Materials or designs to be investigated in the near-, mid- and far-terms.

Components	Materials / Technology	Near	Mid	Far
Power Plant	• Auxiliary resin based / plastic components	X		
	• Replacing iron sleeves w/Al MMC	X		
	• Optimize piston, connecting rod and crankshaft to reduce rotating mass	X		
	• Duel engine design		X	
	• Engine downsizing (20-30% wt reduction)	X		
	• Fuel cells			X
	• Advanced lubricants	X		
Drivetrain	• Topology for gear design	X		
	○ Composite construction (steel teeth pressed onto Al or Mg hub)	X		
	• Drill axial holes in shafts for internal lubrication and reduced weight	X		
	• Advanced bearing design and materials		X	
Cooling System	• Waste heat recovery (e.g. Organic Rankin Cycle)		X	
	• Heat sink material – Al/Diamond, Al/SiC, Boron Nitride, Carbon fiber Al composite		X	
	• High efficiency thermoelectric			X
	○ Micro-composite heat sinks	X		
	○ Nano-composite heat sinks		X	
	• Heat pipes to move heat		X	
	• Nanofluids to increase thermal transfer		X	

Given the broad area of materials and technologies that can be applied to Automotive / Mobility components, the following items are recommended:

5. In conjunction with the design optimization programs, the Army should leverage the materials being developed within the automotive industry and DoE VTO in the near term:
    - Assess how much weight reduction these materials will enable and use the design optimization to guide military-specific materials. Investigate operational energy models and metrics to develop cost metrics for lightweight materials and technologies.

6. Ensure that advanced technologies such as HSUs, cooling system and power plant designs also incorporate weight reduction through material optimization at the component level.
    - Also include alternative approaches such as engine downsizing and waste heat recovery.

7. Invest in far-term Automotive / Mobility alternatives such as fuel cells and advanced suspension designs.
    - Identification of the next big propulsion system, or system layout, that is viable for the Army.
    - Currently the 30- to 35- ton weight goal must be a tracked, rather than wheeled, system. What would it take to enable a wheeled, hybrid, or alternative approach?

Manufacturing Gaps and Recommendations

As in Armor & Structures, joining and advanced manufacturing technologies are critical to light-weighting Automotive / Mobility components. While these technologies will be driven by different materials and component load requirements, the overall recommendations for the Army are the same:

1. The Army needs to increase investment in joining and advanced manufacturing technologies for emerging materials through ManTech and other manufacturing avenues where external (industry, OGA, academia) investments fall short.
    - Require high potential emerging materials to have supporting joining and manufacturing programs.
    - These programs will be driven by the materials developed by the automotive industry and Army R&D efforts, and design optimization assessments.
    - To enable earliest material transition, the manufacturing programs must be executed early on and in parallel to the material development program that they support.
    - Ablation casting is an emerging example that enables a quick quench and improved material properties.

2. The Army needs to engage the national manufacturing centers to ensure that the manufacturing needs of the Army are addressed.
    - Current manufacturing base in several materials of interest are not able to participate fully in ITAR parts.
    - Army has specific material gage needs that are not addressed by any other industry.

Armaments Working Group Summary and Findings

Summary

The Armaments Working Group identified currently funded and proposed programs as high-priority S&T investments for the Army in this area. The highlighted technologies are expected to have the highest impact on reducing system weight while still providing the potential for future overmatch, particularly in the areas of mobility, lethality, protection, intelligence, and mission command. Although these components currently account for a maximum of 15% of the total vehicle weight, a significant percentage of the component weights can be reduced (up to 40%). The primary finding is that since the DoD requirements are the only driver for these materials and technologies, much of the work being done in the Army represents the entire community. To impact the 2030 timeframe, it is recommended that the Army focus new research efforts on design optimization and limited material/manufacturing research, in addition to continuing existing research in certain areas outlined below.

The group recommends the following four areas for Army investment, with a layout of ten programs in these areas shown in Figure 11 (Details on all ten programs can be found in **Error! Reference source not found.**, located in the FOUO version of this document):

1. Invest near-term in understanding the commercial design tools that are available and developing a design optimization approach for weight reduction applicable to Armaments.
    - Use design optimization tools to enable component designs and tailor them to the recoil loads of the system.
    - Design and develop weight reduction packaging envelopes to reduce weight and cost.
    - Leverage commercially available and advanced materials in the appropriate places with designs based on manufacturable geometries.

2. Assess the state of the art in ceramics / CMCs and determine if it is possible to develop the technology for gun bores in the required time frame.

3. Continue S&T investments in energetic material programs to facilitate smaller munitions, with similar energetics to current ammunition and higher P_h and P_k.
    - Low-Cost Hyper-Accurate Weapons (LCHAW).
    - Disruptive Energetics & Propulsion Technology (DEPT).
    - Lethal & Scalable Effects Technology (LSET).
    - Next Generation Close Combat Missile (NGCCM).

4. Continue investment in the advanced manufacturing of Nextel 610 fibers in cast aluminum matrices on steel gun barrels.
    - Research challenges with keeping the steel substrate below its thermal soak temperature, formation of intermetallics at the interface, and galvanic corrosion between Al MMC and steel parts.
    - This manufacturing advancement would enable lighter gun barrels and other components across the vehicle system.

Investment Recommendation Lines of Effort

Figure 11 illustrates the proposed timeframe and investment levels for the ten programs that cover the four areas of Army investment mentioned above. Overall the chart highlights that current S&T investments will lead to an estimated 22% weight reduction, while the additional S&T investments highlighted could increase that reduction as high as 33%. Future S&T investments would be dependent on the decisions made by the BoD. In addition to these ten programs, the critical efforts that need to be executed for the Army to change the way we invest in research and approach weight reduction are highlighted in blue, above the dashed line. These include forming programs to understand the loads that our materials are exposed to, so that we can develop a concurrent design optimization approach for the specific needs of the Army. Additionally, the BoD or a cross-organizational research team needs to engage each NNMI hub to leverage the work being executed under those initiatives and align some of their goals with Army needs. The dashed lines encompass a set of studies that need to be conducted between operational energy models, vehicle concept models, and force-on-force models to develop cost and performance metrics that inform material investments and vehicle design. The next program covers the development of an Armament-specific design optimization, with a tie-in to the Army-wide efforts discussed earlier in this report. With this understanding we will also gain the ability to better invest in a sub-set of materials and technologies that will have the highest impact on weight reduction for this area. These include S&T investments in HSS, CMCs, MMCs, advanced propellants and improved P_h/P_k mechanisms. Finally, the materials selected for investment will then drive advanced manufacturing and joining research, along with demonstrator programs, that should be conducted in parallel with the material research.

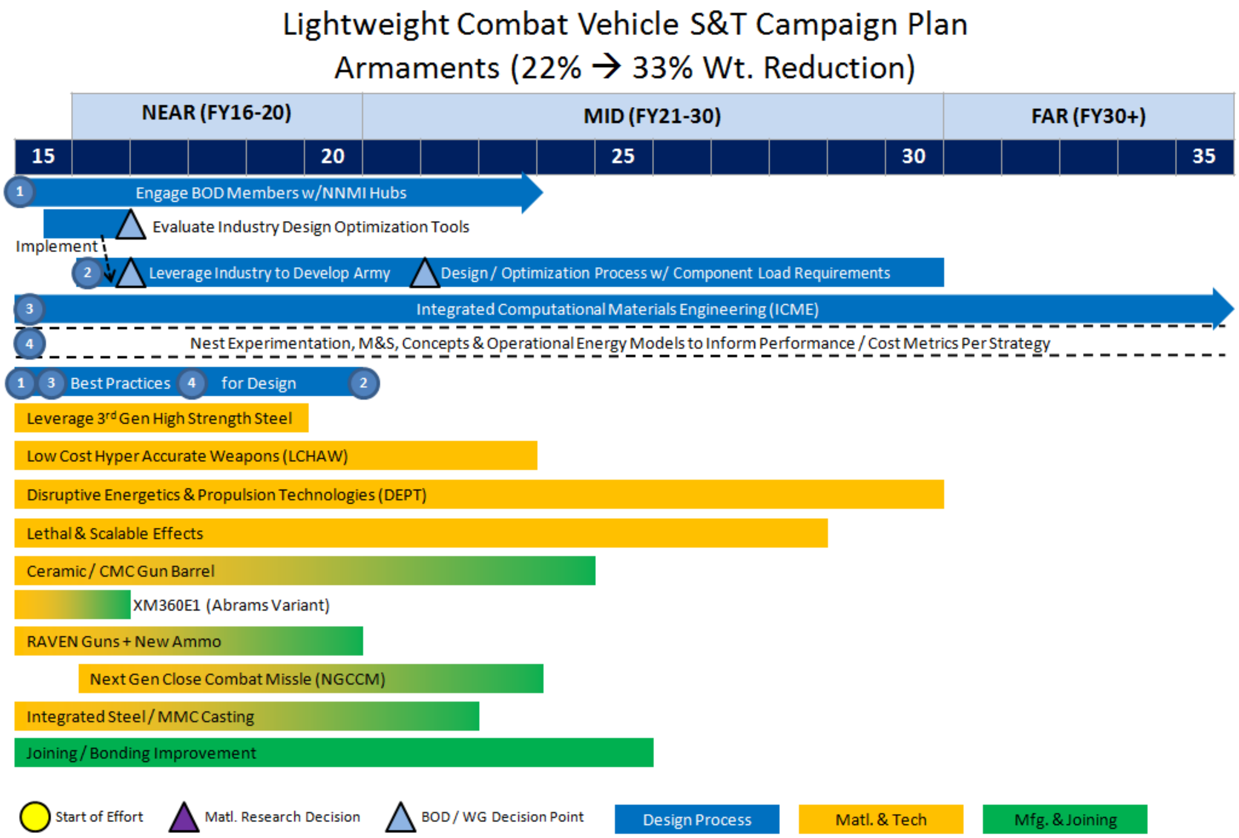

Figure 11. Lightweight Combat Vehicle S&T Campaign Plan for Armaments.

Current Army Programs

At approximately 15% of the vehicle weight for an MBT, the Armaments sub-system represents the third largest category by weight. Unlike other sub-systems, weight is directly related to the performance and operation of the armament system. This is due to the need for absorbing recoil loads while also maintaining gun stability for required firing rates. However, several programs have been executed within the Army that address these performance requirements while reducing weight.

Figure 12 shows existing Army Armament programs, funded and unfunded, that support weight reduction. Unlike other sub-system areas, current Armament programs focus heavily on technologies, products, and manufacturing rather than specific materials that enable weight reduction. However, a significant portion of the product design and manufacturing programs are unfunded (light red). While this limits the number of components addressed in the sub-system, there are still a number of programs across RDECOM that enable weight reduction for specific applications out through 2020.

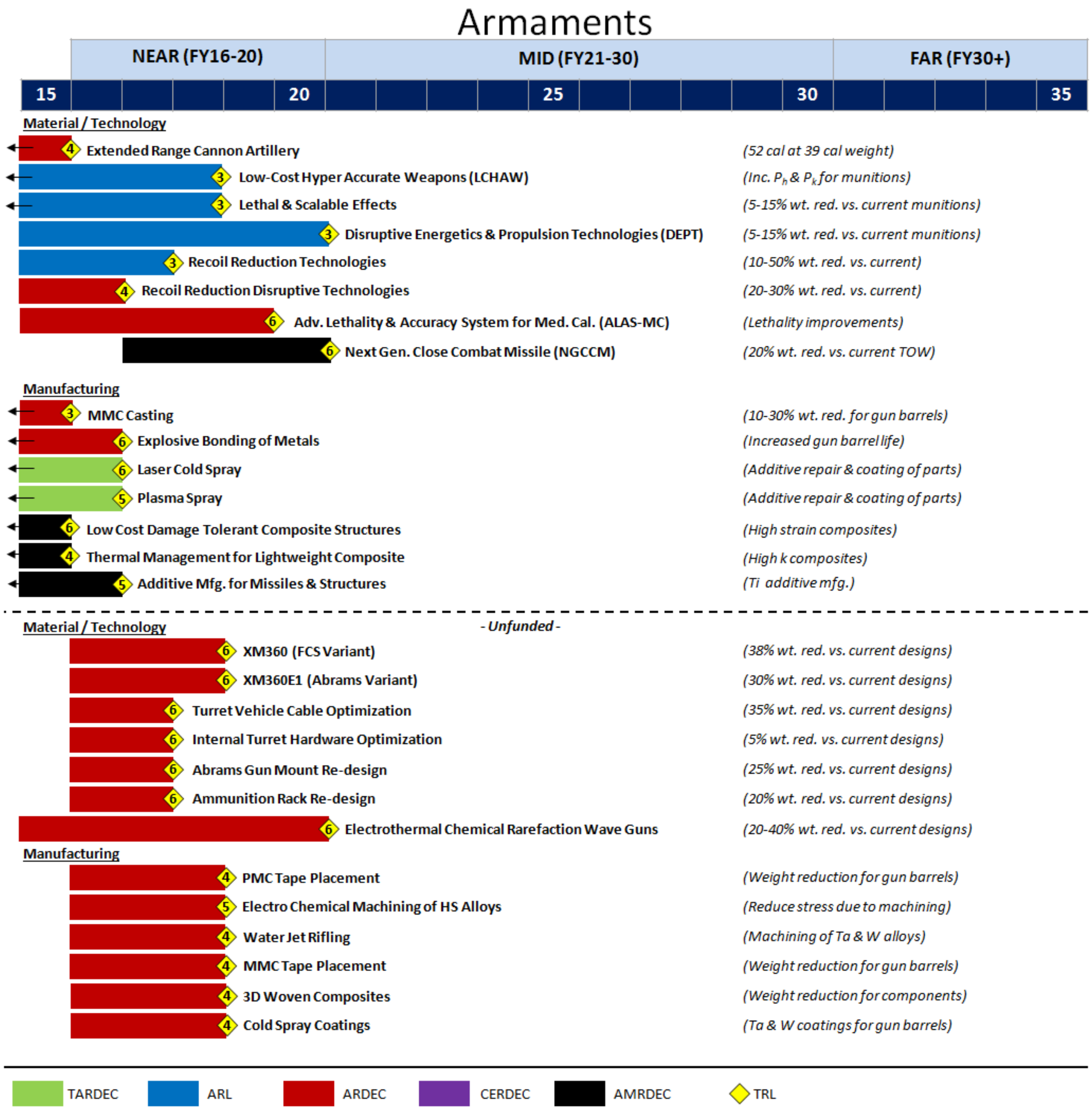

Figure 12. Armament materials, technology & manufacturing Army investments.

Design Gaps and Recommendations

Unlike other vehicle components where increasing strength while reducing weight is the objective (e.g., lightest weight armor to defeat threat), for Armaments, especially large caliber guns, weight plays an important role in recoil mitigation. The kinetic energy of the recoil is inversely proportional to the recoiling mass, and increases with the square of the launch momentum. Thus, if high-strength lightweight guns are developed, while maintaining performance, then muzzle energy/velocity and the kinetic energy of recoil will not be reduced, but will in fact increase. This kinetic energy is transferred to and must be dealt with by the platform on which the gun is mounted. The energy must be fully dealt with and the gun returned to firing position before the next round can be fired.

A traditional system allows the gun to recoil in the mount while applying breaking loads to it. This spreads the energy out over time and thus reduces peak level transferred to the vehicle though the total energy stays the same. There are limits on how long the recoil can be (its stroke is normally under armor) and how long it can take so that the next shot can be fired quickly. Thus, decreasing the weight of the gun tube (the majority of the recoiling mass) makes the job of efficiently handling the recoil energy harder and can result in a higher overall system weight.

Design Optimization

Even when taking the limitations of recoil into account, several best practices for weight reduction can be implemented to optimize the design (Figure 13). Building on lessons learned from the automotive industry, the first four steps (Creating 3D CAD of components; Identify components to optimize; Structurally optimize components; Optimize designs with available materials) can be accomplished using currently available software. It is anticipated design optimization with commercially-available materials (e.g., titanium, aluminum, high-strength steels) will result in considerable weight savings (~ 20%), as evidenced by similar initiatives in the automotive industry. Utilizing a materials-by-design approach (e.g., ICME) could yield weight reductions of closer to 40%, taking into account the use of advanced materials such as anisotropic and novel materials (nanomaterials, composites – ceramic, metal, polymer matrix). Unfortunately, the primary concern for implementing these advanced materials is increased cost due to supply and manufacturing limitations.

Best Practices Process for Light-weighting

1. Create 3D CAD diagrams of vehicle components
2. Identify components to optimize (e.g., recoil tradeoff)
3. Structurally optimize components
4. Optimize using commercially available materials
5. Investigate novel materials
    1. Requires predictive capabilities (M&S, ICME)
6. Optimize structure based upon novel materials
    1. Joint designs
    2. Multi- material designs
    3. Functionally graded materials
    4. Dissimilar material joining

Figure 13. Proposed best practices process for light-weighting.

An example of an optimized design that applied some of these approaches is the XM360 gun assembly, which weighs approximately 4100 lbs. This was an optimization of the M256 gun assembly with composites and high-strength steel, which reduced the weight of the system from 6850 lbs. (a reduction of 2750 lbs., or 40%).

Echoing the design optimization findings from the Armor & Structure and Automotive / Mobility Working Groups, the Armaments recommendation is for the Army to:

1. Invest near-term in understanding the commercial design tools that are available and developing a design optimization approach for weight reduction applicable to Armaments
    - Design optimization will enable component designs to be tailored to the recoil loads of the system
    - Packaging envelopes (i.e., component volume) could be reduced, and thus so could weight and cost
    - Commercially available and advanced materials will be used in the appropriate places with designs based on manufacturable geometries

Materials Gaps and Recommendations

Ceramics

Commercially-available materials (e.g., titanium in place of steel, polymer composites in place of aluminum) can be utilized for design optimization in the near term. There is also a possibility that novel advanced materials currently possessing lower TRLs (such as nanomaterials, or next-generation metal/ceramic matrix composites) can be matured enough for integration in the long term. One such area is the gun bore, which is exposed to high-temperature erosive gas and has historically been protected by chrome plating. Ceramics offer a potential weight reduction solution in this area, and have been shown to be a suitable material for gun bores. While previous gun bore work by ARL and ARDEC identified issues with keeping axial compression on the ceramic during operation, the turbine industry has made several advances in the area of ceramics and ceramic matrix composites (CMC) over the years, and may have overcome the need for tri-axial compression in the ceramic. Thus, a hybrid gun tube with a ceramic or CMC bore and a polymer composite overwrap may be possible; this would provide an extremely light structure.

Energetic Materials

Advanced energetic materials are also of interest in the Armament arena. Although the Working Group focused on material solutions to light-weighting a vehicle in the 2030 timeframe, the group also addressed the topic of maintaining threat overmatch. Maintaining current lethality, protection, and mobility performance may be insufficient when future threats are considered. In addition to possible weight savings, these programs are capable of providing substantial increases in lethality in the future. Currently the Army is investing in several programs in this area. The Low-Cost Hyper-Accurate Weapons (LCHAW) program is focused on ultra-precise, next-generation projectiles with advanced maneuverability and image navigation to increase P_h & P_k. Disruptive Energetics & Propulsion Technology (DEPT) is focused on discovering, inventing, and fully characterizing novel energetic ingredients using chemical and mechanochemical (high pressure) synthesis methods with energy content greater than RDX. These ingredients will then be used in formulations for transition to weapons

applications with significantly improved performance. The Lethal & Scalable Effects Technology (LSET) program is then focused on researching enhanced lethality & warhead mechanisms, enabling technology for kinetic energy lethal mechanisms, scalable effects, and weapons effectiveness analysis. Each of these programs will enable future munitions to be more lethal than current munitions, with a smaller package size and weight. Because the DoD is the only community interested in these systems, there are no outside materials or programs to leverage. Thus, we recommend the Army continue funding these programs jointly with other DoD entities.

An example of an advanced munitions program that will be delivering a reduced weight munition is the Next-Generation Close-Combat Missile (NGCCM). This program is focused on replacing the current Tube-Launched, Optically-Tracked, Wire-Guided (TOW) 2B encased missile with comparable performance, at 80% of the current weight.

Based on the above findings we recommend the Army make the following material and technology investments:

1. Invest in research to assess the state of the art in ceramics / CMCs, and determine if it is possible to develop the technology for gun bores in the required timeframe.

2. Continue S&T investments in energetic material programs to facilitate smaller munitions w/similar energetics to current ammunition and higher P_h and P_k
    - Low-Cost Hyper-Accurate Weapons (LCHAW)
    - Disruptive Energetics & Propulsion Technology (DEPT)
    - Lethal & Scalable Effects Technology (LSET)
    - Next-Generation Close-Combat Missile (NGCCM)

Manufacturing Gaps and Recommendations

Joining Technology

Investigation of the methods of joining materials as an important complement to performing a structural optimization using novel materials one at a time is critical. Many of today's systems utilize conventional joining techniques to join materials, such as nuts & bolts or threads. This leads to additional weight in the armaments system, often with no added benefits (except in the case where modularity is required). Currently, some materials are not very weldable or require the welding of dissimilar materials. In these cases, traditional welding is not an option. Advanced joining techniques are an area which needs considerable investment. Techniques like friction stir welding (FSW) and additive FSW (A-FSW) offer the opportunity to join dissimilar materials with very little heat, hence side-stepping the aforementioned issues with weldability or dissimilar materials. An added benefit is the lack of a heat affected zone (HAZ) which is known to be an area which often leads to failure. FSW is at a fairly high TRL/MRL and has been used in aircraft and space vehicles for decades and should be considered for our systems as well.

Advanced Manufacturing

In addition to the other advanced manufacturing technologies mentioned in the previous sections, a specific need in the Armaments community was identified. Currently ARDEC is also pursuing a next generation howitzer under the Extended Range Canon Artillery (ERCA) program. The goal of ERCA is to develop a 52-caliber 155mm gun system that weighs the same as a 39-caliber system. This requires the use of new materials such as high-strength steel and composites. Of specific interest are Nextel 610 (Al_2O_3) fibers in a cast aluminum matrix, with the goal of casting the MMC directly onto the steel gun barrel. Specific areas of manufacturing research include challenges with keeping the steel substrate below its thermal soak temperature, formation of intermetallics at the interface, and galvanic corrosion between the steel and aluminum. Besides gun tubes this technology allows for fabricating hybrid aluminum MMC / steel parts. This supports the integration of very complex yet lightweight parts, where the MMC represents the majority of the structure and supports the use of steel for specific areas such as connections and multi-axial loading points. Examples include gun mounts, turret baskets, muzzle brakes, and engine mounts.

In addition to the general recommendation for the Army to increase S&T investments in joining and advanced manufacturing technologies, the specific recommendation for the Armament community in the area of manufacturing is:

1. Continue investment in the advanced manufacturing of Nextel 610 fibers in cast aluminum matrices on steel gun barrels.
    - Research challenges with keeping the steel substrate below its thermal soak temperature, formation of intermetallics at the interface, and galvanic corrosion between Al MMC and steel parts
    - This manufacturing advancement would enable lighter gun barrels and other components across the vehicle system

Electronics, Sensors & Other (ESO) Working Group Summary and Findings

Summary

Currently Electronics / Sensors / Other (ESO) sub-system programs are focusing on capabilities and costs. Historically these sub-systems and their components have not been a focus area for weight reduction efforts, as they comprise only 5-10% of the total vehicle weight. Further analysis is required to identify the distribution of the weight in the ESO sub-systems among cabling (power and data), power conversion and distribution, computers, enclosures, connectors, displays, sensors, and communications components. The commercial automotive and aerospace industries, along with the military aerospace industry all have significant interest in the reduction in weight of these components, looking to provide greater fuel economy, range and payload capacity.

However, in the DoD ground vehicle environment the more strenuous environmental test conditions for temperature, shock and vibration combined with military specific processing and sensing requirements move many of the DoD components of interest outside of the area of interest of the automotive industry. Aligning military ground vehicle ESO weight reduction efforts with the commercial and military aerospace industries presents a challenge because historically aviation has traded cost in favor of weight and ground vehicles have traded weight in favor of cost. This dynamic is critical for aircraft because an overweight aircraft will not get off the ground, will reduce its operational range, and will not be capable of safely landing. In ground vehicles this is commonly seen in the material choices for structural components where heavier lower cost components are commonly chosen to provide similar performance to lower weight higher cost materials.

The Army's primary S&T investments in electronics architecture is the Vehicular Integration for Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR)/Electronic Warfare (EW) Interoperability (VICTORY) initiative, which looks to remove redundant components from the vehicle by providing a common infrastructure and sharing of components. Further S&T investments include the development and manufacturing of new materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) to produce higher temperature electronics.

The team recommends the following areas for Army vehicle architecture light-weighting investment:

1. Vehicle architecture consolidation efforts
   - Metals and Semiconductors: Carbon Nanotubes (CNTs), Graphene, Gallium Nitride and SiC are expected to reduce power requirements and could increase operational temperature eliminating the weight of required cooling systems and additional equipment.
   - Novel Electronics: The use of Conformal / integrated components, flexible displays and multi-function sensors will enable new more compact packaging designs reducing the under armor volume and hence total vehicle weight.
   - Alternate Power Generation: Harnessing shock compression motion from the vehicle to power small sensors or electronics will reduce the power distribution cables and the weight they add to the vehicle.

- Share Processing Capacity: In conjunction with common architecture and elimination of electronics redundancy, enable multiple electronics packages to share common power and processing capacity to reduce power consumption and packaging space.

Investment Recommendation Lines of Effort

Figure 14 illustrates the proposed timeframe and investment levels for the Army ESO programs. Overall the chart highlights that current S&T investments will lead to an estimated 24% weight reduction, while the additional S&T investments highlighted could increase that reduction as high as 27%. Future S&T investments would be dependent on the decisions made by the BoD. In addition to these S&T investments, the critical efforts that need to be executed for the Army to change the way we invest in research and approach weight reduction are highlighted in blue, above the dashed line. These include forming programs to understand the loads that our materials are exposed to during operation (e.g., automotive shock and vibration, structural loading during ballistic events, etc.), so that we can develop a concurrent design optimization approach for the specific needs of the Army. Additionally, a BoD or similar functioning group needs to be formed so that they can engage each NNMI hub to leverage the work being executed under those initiatives and align some of their goals with Army needs. The dashed lines encompass a set of studies that need to be conducted between operational energy models, vehicle concept models, and force-on-force models to develop cost and performance metrics that inform material investments and vehicle design. The next program covers development of ESO-specific design optimization for lightweight ruggedized enclosures, which ties into the previously mentioned Army-wide efforts. Material and technology investments are also laid out in the Plan, including S&T investments in SiC, GaN, CNTs, graphene, novel electronics (e.g., flexible displays, integrated components, and so on), alternate power generation, and architecture and shared processing. Although not explicitly identified as a separate effort, the materials selected for investment will then drive advanced manufacturing and joining research, along with demonstrator programs, that should be conducted in parallel with the material research (similar to those laid out in the Armor & Structure section).

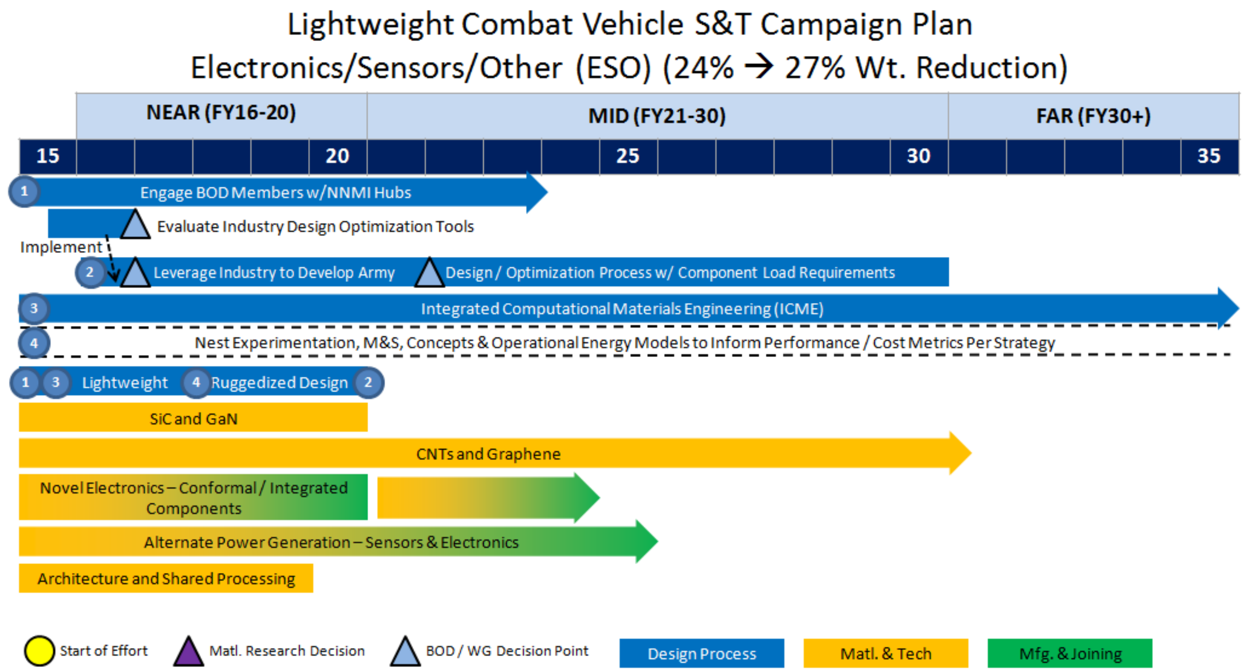

Figure 14. Lightweight Combat Vehicle S&T Campaign Plan for ESO.

Current Army Programs

Electronics / Sensors / Other (ESO) sub-systems represent the remainder of the vehicle components and account for 5-10% of the total vehicle weight. As with other sub-systems, the working group reviewed existing Army programs in ESO that support weight reduction (Figure 15). Programs within ESO focus on architectural improvements to remove redundant components, materials for electrical components to reduce SWaP, and reduced electrical power consumption.

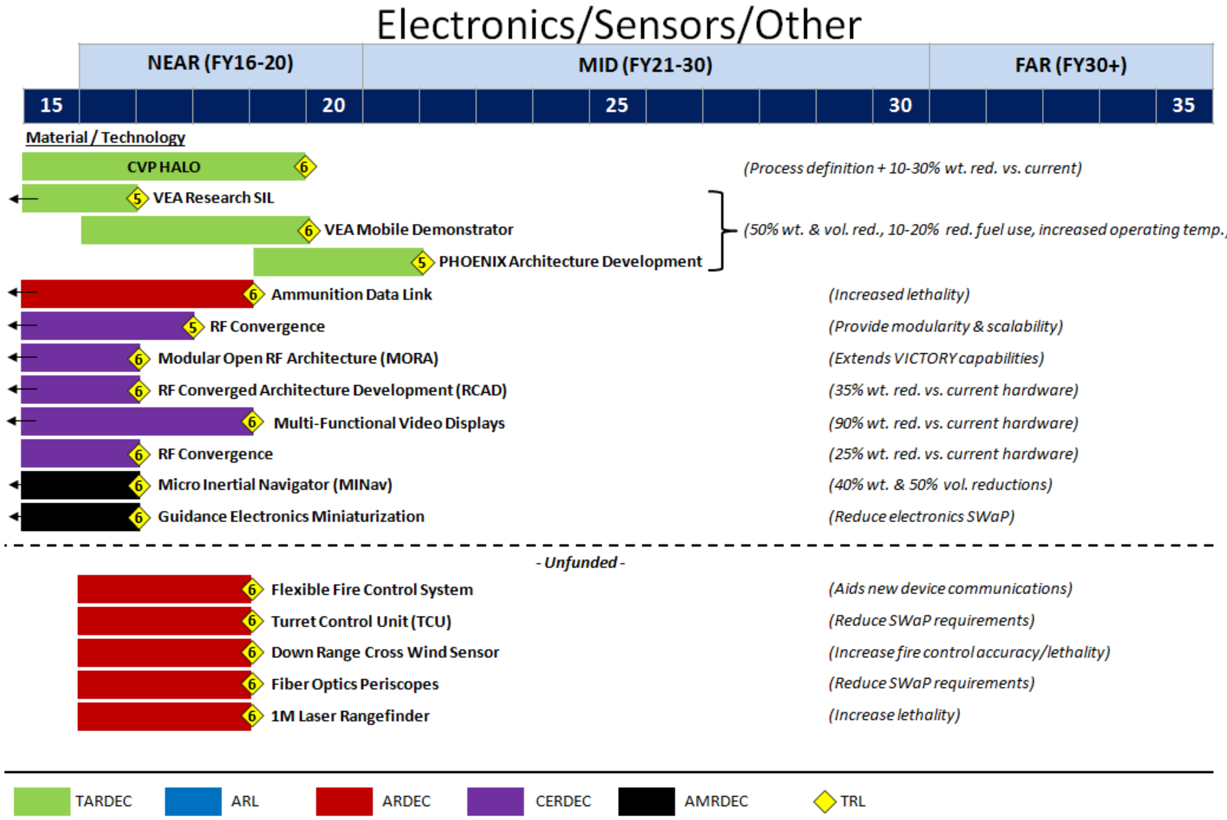

Figure 15. ESO material, technology & manufacturing Army investments.

Working Group participants for Electronics, Sensors and Other (ESO) represented the diverse composition of the workshop participants, having experts in the fields of material science, manufacturing, armaments, and vehicle mobility. Experts applied their knowedge to the issue of reducing the Size, Weight and Power (SWaP) requirements of electronics systems, and provided a valuable perspective on the problem. The goal of the ESO Working Group was to address the question, "What steps can we take using Electronics, Sensors or Other means to produce a significantly lighter ground combat vehicle with performance equal to or greater than current systems?" as it relates to the vehicle electronics and sensing capability.

Due to the diverse background of the ESO sub-group participants, the first of the four discussion sessions were spent familiarizing the group with the current capabilities, limitations and needs associated with Electronic and Sensor systems. The importance of sensors, power, cooling, and integration were of particular note for these discussions.

Discussion

The current fleet of Army fighting vehicles are designed as weapon platforms and troop transportation assets. Integration and operation of sensors and electronics systems has typically been done in an ad

hoc manner, resulting in bolt-on solutions that are not optimal in terms of SWaP or system performance.

The Working Group's discussions identified four main areas where potential weight savings could be gained while maintaining or improving performance of platform sensing and electronic capabilities:

- Reduce Redundant Components
- Change Cooling Approaches
- Reduce power consumption
- Reduce Enclosure Weight, Cabling Weight, and Connectors

Reduce Redundant Components

Current systems lack a vehicle architecture that supports electronic system integration; thus, each new component that is integrated into a platform must provide all of its necessary functionality. This integration philosophy has frequently resulted in redundant resources being implemented in a platform, causing the SWaP for electronics and sensors to be unnecessarily inflated. A simple example is that every system on a platform requiring a GPS input typically brings its own independent GPS resources to integrate. This results in multiple redundant GPS assets on a platform. Other redundant capabilities include displays, processors, power and RF distribution. A remedy for this problem is the development of an electronic system integration architecture which provides shared resources and services. Current efforts work to mature and expand the VICTORY program defining such architecture and is already at TRL 5. The VICTORY Enabled Company Transformation (VECTOR) project is developing the vehicle implementation of VICTORY which will mature the technology to TRL 6. There is very little risk associated with this approach; which could have an estimated SWaP savings of 5 -10% of the ESO weight.

An example of redundancy reduction was applied in TARDEC's Ultra Light Vehicle (ULV) Research Prototype (Technology Demonstrator), as seen in Figure 16. The ULV design utilizes consolidated vehicle electronics/GFE packaged in the rear of the vehicle; data is routed through a single data distribution system outputting information to tablet-like displays to the driver, truck commander, and gunner positions. This reduces weight, heat and secondary projectiles to the crew compartment while allowing for increased interior space. While only an initial look at this type of design, the ULV highlights some of the reductions that can be made in future vehicle designs.

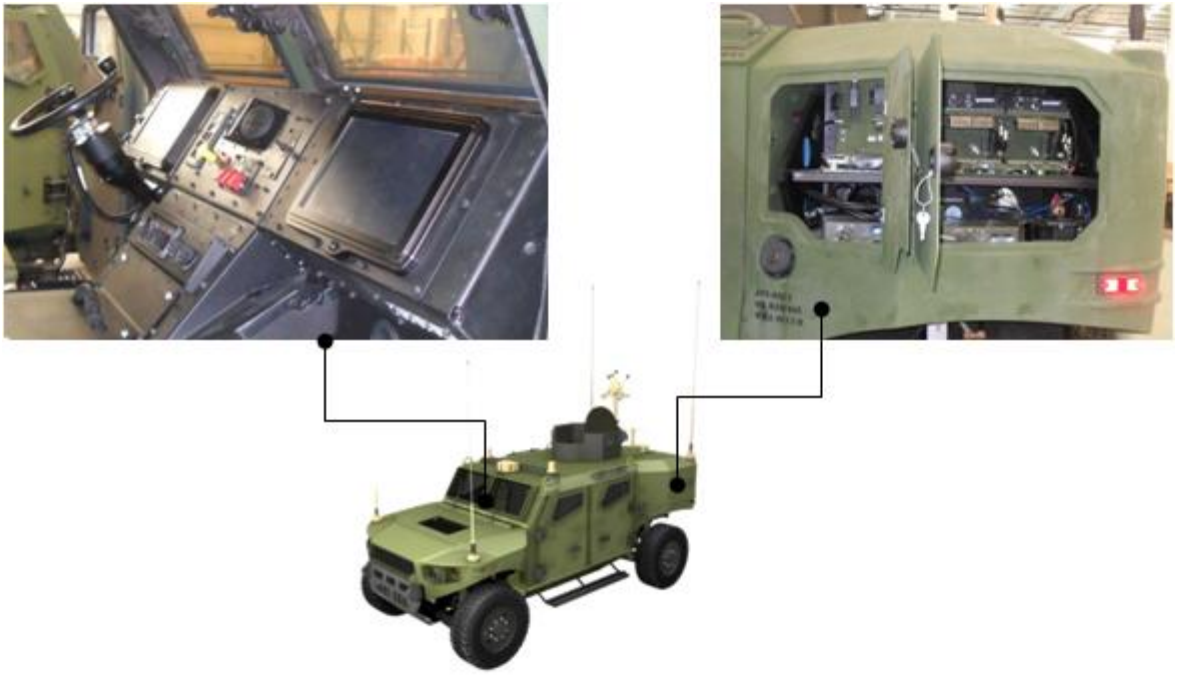

Figure 16. ULV example (TARDEC).

As shown in Table 10 below, concepts to reduce weight are not necessarily material-driven. Most of the concepts identified shared a common theme of finding innovative ways to define architectures and components to reduce redundancy. This table depicts other potential S&T investments that may provide SWaP savings on the platform.

Table 10. Potential investments for platform SWaP savings.

Concept	Status
Define an architecture that allows for common components and data to be shared (E.g., GPS data, displays, processors)	VICTORY and VECTOR currently TRL 5: Additional development required to realize possible SWaP reductions. On track with current investment to be TRL 6 by 2015
Eliminate direct redundancy (E.g., Systems can share displays)	Currently TRL 5: Current investment working to define interfaces for display application development. On track with current investment to be TRL 6 by 2015
leverage Industry Consortia **Share processing capacity**	Currently TRL 3: Industry consortium is providing additional resources to extend SW development framework. Government investment is necessary to integrate into future POR development (estimate $2M/year from FY15-20)

Change Cooling Approaches

The need for increased power and processing capabilities on vehicles are beginning to exceed our ability to cool these components using only convection or air-cooling methods. As a result, integration of greatly increased electrical and electronic capabilities also necessitates the integration of additional

electronics liquid cooling capacity. There are several on-going areas of R&D that could reduce the SWaP impact of liquid cooling requirements for various electrical and electronic systems.

1) Developing and maturing the use of Silicon Carbide (SiC) and Gallium Nitride (GaN) materials for heat-tolerant electronics,

2) Utilizing the automotive system liquid cooling loop to cool SiC based power electronics.

Silicon Carbide (SiC) can replace Silicon in the development of high voltage electronics and Gallium Nitride (GaN) can replace Silicon in the development of low voltage electronics which can operate at higher temperatures, greater efficiency and higher switching frequencies. This will allow for the development of power electronics which have a greater power density leading toward a 30-40% reduction in weight when compared to a traditional silicon based component.

The higher operating temperature of Silicon Carbide and Gallium Nitride allows for the shared use of the liquid cooling used by the automotive system. By sharing the automotive cooling system, greater heat dissipation capacity is created for the electronics without adding an additional cooling loop to the vehicles; this provides a weight neutral solution while increasing the power generation and distribution capacity of the vehicles. Table 11, below, provides a high-level overview of these topics.

Table 11. : R&D efforts that may reduce cooling requirements for various electronics.

Concept	Status
Use the automotive liquid cooling system to create a common cooling bus	Current TRL4: Current projects are proving out the operation of SiC power electronics operating with the use of higher liquid cooling temperatures
SiC and GaN Heat-tolerant electronics	TRL 5: DoD has invested over $80M in the development, and manufacture of SiC electronics Commercial industry is already investing in the development of GaN electronic components

Reduce Power Consumption / Improve Power Generation, storage, efficiency

To reduce power consumption while improving power generation, storage, and efficiency, the Working Group recognized that the growing demand for processing and sensor capability leads to an increase in power draw on the platform, outpacing the platform’s ability to generate that necessary power, based upon MIL-STD-1275 28V power. These concepts, illustrated in Table 12, include materials and methods that may improve vehicle power generation, improve vehicle power management, and/or provide alternate power. They may also improve peak power as an added benefit.

Current military vehicles use 28V power for generation, storage, and powering equipment. The increasing demands for electrical power on vehicle require increased generation. Generating increased power at 28V is reaching its technical limit based upon component size and cooling, and distribution cabling sizing. The use of higher voltages such as 600V increases opportunities to reduce cabling size and weight.

Improving peak power storage focuses on the use of other battery chemistries to reduce vehicle weight. A pair of the current HAWKER 6TAGM lead-acid battery weighs 176 lbs total. Battery chemistries such as lithium ion have the potential to provide a weight savings of 50% over a comparable lead-acid battery. Other future battery chemistries could provide additional weight savings at increased power densities.

Providing alternative power generation is an attempt to provide additional electrical power, while removing loads from the vehicle's engine. This approach provides an opportunity to reduce the size and the weight on the vehicle engine, but requires the vehicle to have a hybrid design. Issues with this approach are that these concepts are small component inputs that either don't scale well when applied to big vehicle problem, or may scale but the cost of scaling is greater. Energy-informed operations provide an avenue to reduce the need for power and fuel on the vehicle platforms by monitoring and controlling its use. The vehicle electronics community is currently investigating are approaches to shut down vehicle engines automatically when idle, and allowing necessary vehicle systems to run on battery power. This technique, commonly used in European passenger automobiles and U.S. hybrid vehicles, provides a path to reduce the amount of fuel consumed for a given mission profile, which then reduces the amount of fuel carried on vehicle. Another opportunity is the use of power management to shut down large power loads such as air conditioning, which provides the potential to reduce the size and weight of the vehicle's engine or its power generation equipment. Currently the Army is executing projects to investigate both methods.

Additional research and SME input is required into these areas to more thoroughly understand potential weight saving and investment requirements.

Table 12. Concepts addressing power generation, storage, and efficiency.

Concept	Status
Energy-informed operations on platform	Currently TRL 5: Current projects are investigating anti-idling technologies to reduce fuel consumption this is expected to be at TRL 6 by 2015. Power load management is expected to be TRL 5 by 2015 and TRL 6 by 2019.
Power storage for peak power needs	Currently TRL 5: Current programs are testing lithium ion solutions for Naval Transport providing at TRL 6 solution.
Alternate power generation on platform (e.g., harness shock compression motion, heat output from engine etc.)	Need additional SME input to quantify investment requirement and future TRL status (sources: ARL, CERDEC/CPI, Industry and Academia)

Reduce Enclosure Weight, Cabling Weight, and Connectors

The team recommends pursuing several different methods of material weight reduction for electrical, electronic and sensor components (Table 13). The enclosures can be produced using composite materials. The use of high-voltage power will allow the vehicle's power distribution cabling to be reduced in gage and weight. The use of fiber-optic cables for data distribution presents another avenue

to reduce cabling weight. The reduction in connectors on each enclosure can also reduce the weight, enabled by the definition of the vehicle's architecture.

Enclosures for electronics provide protection, enable convection cooling, and provide Electromagnetic Interference (EMI) protection. The use of composite materials may provide an opportunity to reduce the weight of the enclosure while providing necessary EMI shielding. The design of the enclosure can be optimized for weight reduction by using commercially available software

The need for power continues to increase on vehicle platforms to support an ever-increasing array of electronics and sensors. The increase in power at the low voltage of 28V drives an increased wire and cable sizing and weight. The shifting from 28V power to the higher 600V voltage of provides a mechanism to produce more power while reducing the sizing and weight of both wire and cable.

The use of fiber-optic cabling provides another mechanism to reduce the weight by eliminating or reducing the amount of heavy copper data cables. Fiber-optic connectors are also lighter than other cabling connecters and provide additional weight savings. Military fiber-optic connectors can provide a weight reduction of 17-70% compared to MIL-DTL-38999 connectors.

The development of a common electronics architecture like VICTORY provides a mechanism to reduce the number of connectors that exist on a single electronics enclosure. Military connectors can weigh between 0.1 lbs to 0.5 lbs per mating pair, with some enclosures having upwards of 10 connectors. Under VICTORY architecture guidelines, many of these enclosures could have as few as 2-3 connectors.

Novel electronics such as flexible/conformal displays and components also offer opportunities for weight reduction. In addition to being thinner than current designs, these technologies offer reduced armor weight by requiring a reduced package volume and enabling previously unavailable integration locations.

Table 13. Investments addressing reduced enclosure, cabling and connector weight.

Concept	Status
Lightweight ruggedization packaging	Need additional SME input to quantify investment requirement and future TRL status (sources: ARL, Industry and Academia)
Novel electronics and processing, Flexible displays, Conformal/ Integrated components, Multi-function sensors	Need additional SME input to quantify investment requirement and future TRL status (sources: ARL, Industry and Academia)

Weight Analysis

Based on the review of material and technology development efforts throughout the Army, other government agencies (OGAs), industry and academia, the team calculated the anticipated weight savings for future MBT and IFV programs near 2030. This calculation was based on the baseline weight tapes for the Abrams M1A2 SEP and the Bradley M2A3 (see "Baseline Subsystem Weights") but is not meant to be a weight reduction analysis for those vehicles. Full weight tape detail is provided upon request; only high-level weights are provided here for review. The analysis took into account anticipated weight reductions due to design optimization and material substitution for each system component. However, it should be noted that these values are only estimates, since so much of the vehicle weight, and thus weight reduction, is based on the vehicle design. All technologies that could provide a weight reduction without a change to operational doctrine were included (e.g., HSUs to replace the torsion bar suspension). While the weight-reduction assessment illustrates where the material and technology advances can reduce ground combat system weight in the future, this analysis requires the following assumptions:

1. Generic weight-reduction values were used for design optimization, because actual optimization studies were not conducted.

2. Without conducting actual design optimization, the analysis could not take into account the effect of weight-reduction compounding between optimized design and material SWaP.

3. Material swaps assumed a "ballistic equivalent" solution (where applicable) in the weight reduction estimate, but increases in system volume were not assessed.

4. All material weight reductions assume the "maximum reduction possible" is achieved, and that unforeseen integration and material science issues are not encountered.

Table 14 shows the weight analysis of a future MBT. Based on theoretical, high risk material and technology substitutions, roughly 19 tons could be shed from the current vehicle design, while still maintaining performance. This assumes that current S&T investments yield the optimal weight reduction by 2030. Taking the recommended S&T investments into account in addition to the current investments, another 12 tons of weight could be shed. Again, these are high-risk predictions based on current material and technology weight reduction estimates being achieved by 2030. While it does appear possible to create a 45-49-ton MBT design by 2030, this vehicle weight still remains at least 10 tons above the 35-ton goal. The additional 22% of the desired weight savings will need to come from additional technologies or designs that could impact doctrine.

Table 14. Weight analysis for future MBT.

Description	Baseline	Current Investments	Current + Recommended Investments
Hull	48,677	36,293 – 38,726	29,988 – 32,422
Suspension	24,025	14,907 – 16,108	6,081 – 7,283
Power Plant & Drivetrain	11,038	9,382 – 9,934	8,261 – 8,813
Auxiliary Automotive	4,833	3,432 – 3,673	3,360 – 3,601
Turret	49,130	38,929 – 41,385	31,738 – 34,195
Fire Control	3,777	2,526 – 2,715	1,835 – 2,024
Ammunition	3,787	3,218 – 3,407	3,218 – 3,407
Other Vehicle Equipment (OVE)	3,498	3,143 – 3,318	3,076 – 3,251
Crew	836	836	836
Fuel	3,048	2,286 – 2,438	2,286 – 2,438
Gross Vehicle Weight (lb)	**152,649**	**114,952 – 122,541**	**90,679 – 98,270**
(Tons)	**76.3**	**57.5 – 61.3**	**45.3 – 49.1**

Table 15 shows a similar weight analysis for a future IFV. Leveraging current S&T investments and assuming the maximum weight reduction for the advanced material and technology substitutions, roughly 7 tons could be shed from the current design. Applying the recommended S&T investments in design optimization, materials and technologies in addition to this would enable another 3 tons to be removed from the gross vehicle weight. This gives a total vehicle weight of 29-31 tons which is at the goal of 30 tons. Thus, while high-risk, it does appear possible to design a 30-ton IFV by 2030 with the current capabilities and requirements.

Table 15. Weight analysis for future IFV.

Description	Baseline	Current Investments	Current + Recommended Investments
Hull	37,551	30,206 – 32,083	26,139 – 28,016
Suspension	12,273	10,196 – 10,809	9,219 – 9,833
Power Plant & Drivetrain	6,870	5,728 – 6,072	5,262 – 5,606
Auxiliary Automotive	4,416	3,634 – 3,855	3,474 – 3,695
Turret	7,501	6,242 – 6,617	5,033 – 5,408
Fire Control	2,538	2,490 – 2,538	2,490 – 2,538
Ammunition	2,561	2,185 – 2,313	2,185 – 2,313
Other Vehicle Equipment (OVE)	1,351	1,306 – 1,351	1,267 – 1,335
Crew	2,200	2,200	2,200
Fuel	1,325	995 – 1,061	995 – 1,061
Gross Vehicle Weight (lb)	**78,585**	**65,182 – 68,899**	**58,264 – 62,005**
(Tons)	**39.3**	**32.6 – 34.4**	**29.1 – 31.0**

While all of the assumptions made in this analysis represent the maximum weight reduction for high-risk S&T investments, a few additional caveats must be understood. First, much of the weight reduction will be driven by the actual vehicle design and how each of these S&T investments can be applied to that design. Second, as with historical vehicle weight trends, if the threat-set for these future vehicles increases significantly, so will the vehicle weight. Finally, the cost metrics for the proposed future vehicles will drive which materials and technologies will be inserted into the final design. If there are cost barriers that cannot be overcome, many of the anticipated weight savings will not be implemented by the Army.

Non-Material Science Approaches to Light-weighting

In order to get an MBT down to the 35-ton weight goal from the 45.3-ton weight that is potentially achievable through advances in material science, the Army must apply additional technologies and approaches. Besides the direct weight-reduction technologies associated with material science, manufacturing, and design that have been outlined in this report, there are vehicle-level architectures and technologies that can have a significant impact on vehicle weight. Some of these technologies mitigate the need for weight (e.g., reducing under armor volume, unmanned systems) or provide greater customization as to the weight carried by the vehicle (e.g., modular protection). However, these changes in technologies also require adjustments in the Army's doctrine. While technologies that require a doctrine change were not considered in the Lightweight Campaign, it has been recognized that to meet the 35-ton objective, we need to be open to all technologies that can reduce weight. This section gives an overview of some of the technologies and potential weight savings that can be applied to future system designs.

Modular Protection

Modular armor kits are not new. However, one approach that has not yet been fielded is to design vehicles and vehicle structures to support the concept of modular protection and ease material technology trades (Figure 17). This approach would separate the structure (A-level) from the armor or protection system. In the past, it was considered more weight-advantageous to integrate structure and armor, since ballistic loads typically exceeded structural loads. This led to an integrated armor hull to double as a structural hull. This approach only allows armor to be added to the existing hull because it is not cost-effective to change the integrated structure-armor system (hull). Complete vehicle disassembly is required to upgrade the structure to accommodate new technology under this paradigm, which is cost-prohibitive. The Modular Protection approach has four major advantages over the legacy paradigm:

1. Scalable Protection – depending on the mission threat level, a vehicle's protection level and associated weight can be quickly scaled up or down simply by adding or removing armor kits (~20 tons of removable armor).

2. Future Armor Upgrades – As lighter-weight ballistic materials are developed, they can be introduced by replacing armor kits, which is easier to do than to modify inherent vehicle structures.

3. Protection Technology Adaptation – as new protection technologies mature, armor kits can be modified (as opposed to vehicles) to address new threat defeat reallocation.

4. Depending on the structural architecture, it may be possible to reinforce the structure locally as new stresses from future systems arise (large guns, differing loads, and advanced armors).

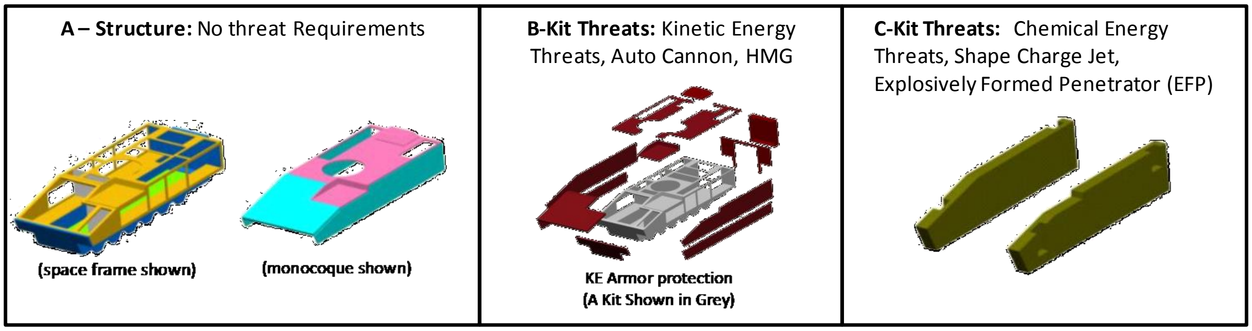

Figure 17. Modular protection.

Adaptive Protection

Adaptive Protection provides a variety of technologies that enable the vehicle to react to a threat in real time, thereby improving occupant protection and mitigating the need to provide the same level of protection through passive armor systems alone. These systems work in conjunction with passive armor systems. However, if adaptive systems were not to be developed, then the amount of passive armor required to stop future threats would vastly increase the weight of the vehicle. The anticipated weight savings for implementing Adaptive Protection on a heavy combat vehicle range from 8-13 tons. The major systems included here are:

1. Advanced Sensors capable of 360-degree hemispherical coverage on both the interior and exterior. These sensors are necessary to trigger the additional responses required to keep the occupants safe.

2. Balanced Active Protection System (APS) / Armor Systems consisting of hard, soft, and passive defeat solutions, each designed for specific threats. Some of these systems might be reactive and adaptive armors and APS.
3. Integrated Crew Systems, such as reactive restraints, inflatable bags, seats, and active fire extinguishing systems.

4. Vehicle level responses are systems that enable the vehicle to move in such as way as to reduce the impact of the threat, such as morphing suspension systems, counter-blast systems, and advanced structural integrity systems.

Reduced Under-Armor Volume

Since armor and structure remain the primary weight contributors, any technology that can reduce the amount of volume that needs to be protected by armor can indirectly reduce the weight of the vehicle. For example, on a large infantry-carrying combat vehicle, each linear inch of under-armor volume results in an additional weight of 80-250 lbs. Thus, choosing a transverse engine over a linear-mounted engine could potentially save 36 inches of under-armor volume resulting in 4.5 tons of weight savings.

Unmanned Systems

In manned systems, the need to protect the occupant is paramount; much of the armor on the system exists to protect the human crew members. Unmanned systems, by contrast, offer the potential for substantial weight-reduction because there is no human occupant. This approach would require investments in other technologies, such as sensors, software, and controls, but the overall logistics cost savings over the lifetime of the unmanned system could repay this investment.

This is not an argument to move to all unmanned systems. But, in combination with manned systems, certain task functions could be automated to require fewer people to do as many tasks. Fewer people would result in reduced under-armor volume, or the addition of a completely different class of lighter-weight vehicles. For example, a current Abrams Platoon consists of 4 vehicles, 16 crew, and weighs about 304 tons (see Figure 18). By comparison the Main Battle System (MBS) consists of 2 manned supervisory vehicles which are armored at a level to protect the crew, and 4 unmanned direct fire vehicles which are armored to protect the vehicle (that is, less heavily armored than the manned vehicles). These systems could potentially be 30%-60% lighter, because the supervisory vehicles will not be subjected to the same threats as the direct fire vehicles, and the direct fire vehicles will not require the crew space or the occupants' safety protection systems.

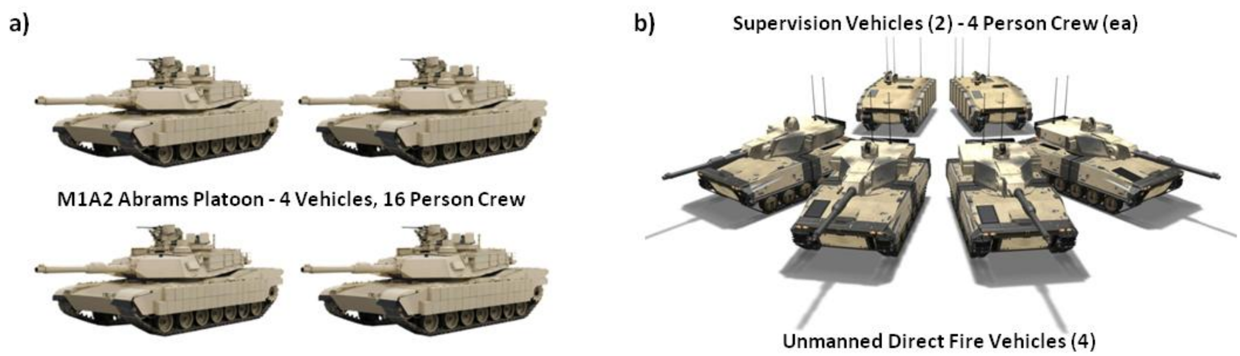

Figure 18. Abrams and Main Battle System (MBS) platoons. a) Current M1A2 SEP Abrams platoon is 4 vehicles, 16 crew, and ~304 tons. b) Conceptual MBS platoon with 6 vehicles, 8 crew, and ~100-200 tons.

Advanced Vehicle Architectures

Different vehicle architectures could also potentially have a large impact on total weight. Developing modular vehicle platforms capable of utilizing different mission modules could be a weight savings initiative if the vehicle utilizes only those modules required for the mission (see Figure 19). An articulated vehicle (see Figure 19) would be another way to achieve mission flexibility at potentially lighter weight. In an articulated vehicle the vehicle, functions are allocated to various vehicle modules. Each module can then be weight-optimized, potentially eliminating or reducing the under-armor volume, or the need for other systems that may not be necessary for that particular module to meet its mission. It is not yet possible to determine the weight savings from these types of alternative vehicle architectures. For a given configuration they are likely to be overweight due to the module integration hardware. However, given their mission flexibility and assuming that not all vehicle functions/ modules will be necessary for all missions, the impact to operational energy and logistics could be significant

when considered as a system over the length of a deployment; given the particular and relevant scenario.

There are also other major vehicle architecture considerations. For example, vehicles that are fully electrically operated and do not require any hydraulics for suspension or otherwise could potentially be significantly lighter.

These are some examples of the types of large system / architecture considerations that could have a significant impact on weight and operation. It is impossible to say how much lighter these vehicles could be without working out a complete concept (see next section). However, it is known that design considerations cast the largest shadow on product cost and performance, and that vehicle architectures cast the largest design shadow.

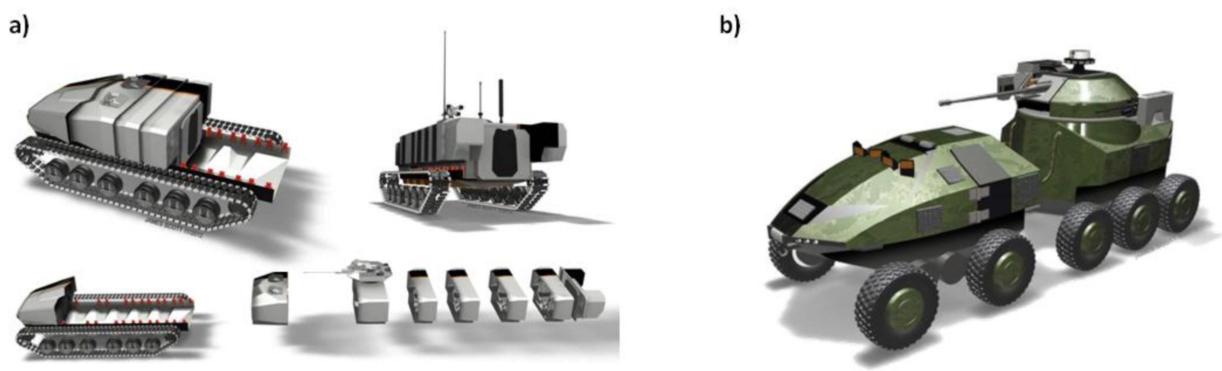

Figure 19. Modular and articulated vehicle designs. a) Tracked vehicle with modular mission packages. b) Articulated wheeled vehicle design.

Advanced Armament Systems

The Rarefaction Wave Gun (RAVEN) (seen firing Figure 20) is a revolutionary new gun concept being developed by ARDEC. With RAVEN the breech is opened while the projectile is still in bore. This allows for the venting of propellant gasses rearward to reduce the recoil force by 75%. This enables a large-caliber weapon to be mounted to a vehicle platform that weighs much less than 35 tons. If this venting is delayed until the projectile is 24% down the bore, the rarefaction wave created by the venting never reaches the projectile before shot exit. This means no loss in projectile performance. Additionally, since the hot propellant gasses are exiting out the breech instead of lingering in the bore, this reduces heat input to the front half of the gun by 50%. With the reduced heat loads, previously unusable polymers could be leveraged in the construction of the gun, further reducing the weight.

Figure 20. Rarefaction wave gun (RAVEN).

Unfortunately, the RAVEN cannot simply be swapped in for a traditional cannon. The rearward venting of the propellant gasses necessitates that the gun be mounted outside of the turret. Being outside of the turret will require an autoloader and by extension the removal of the traditional loader position. The duties associated with that position would have to be handled by the remaining crew or new technologies. While this constraint has kept this technology from being pursued by legacy systems, a clean-sheet approach to vehicle design could incorporate this technology with associated under-armor weight savings.

Although new ammunition would need to be developed to take full advantage of this gun design, it would then become possible to have straight-chamber ammunition with current 120mm performance in a 105mm form factor. This not only allows for a smaller overall gun tube, but also allows for either a reduced ammunition magazine or more stowed rounds. Combining the reduced recoil force, reduced heat loads and advanced ammunition, it is estimated that the RAVEN weight savings over current gun systems would be well beyond 50% without sacrificing performance.

Next Generation Close Combat Vehicle Study: Large Caliber Indirect/Direct Fire Vehicle

Utilizing many of these capabilities, the Next Generation Close Combat Vehicle (NGCCV) study is currently investigating several potential vehicle designs that are lighter than the current combat force.

In support of TRADOC's need for a more expeditionary future force, TARDEC is leading the NGCCV study to assess and identify technology combination-suites that can result in the development of lighter-weight and effective combat vehicles. NGCCV is investigating a combination of material science (from the LCVSTC) and enabling technologies that could potentially result in changes to doctrine. These two efforts, along with Capability Demonstrations in TARDEC's 30-Year Strategy as supported by Combat Developer input, will be used to support the development of a strategy laying out a probable-realistic

set of materiel options that can be evaluated, modified and pursued as appropriate to reduce future force vehicle weights.

Below is an example of the concepts developed in the NGCCV study that could be leveraged for a future MBT. While the individual mission role concepts are currently in process, an example of the technology and automation contributions to weight reduction should be illuminated in the final NGCCVS results with an initial look at three (3) different approaches to the Direct/Indirect Fire mission. The first approach is a Class III (~30 Ton deployment weight) direct/indirect fire concept which includes a platform with a two man crew and large caliber weapon on a Class III platform that allows for some level of tank KE protection. The other two concepts for the Direct Fire/Indirect Fire role are on the Class II platforms (~15 Ton deployment weight). The second approach is a two-man crew concept which includes a smaller caliber assault gun without tank KE protection. The third concept is an unmanned concept incorporating a large-caliber, lower-recoil cannon also without tank KE protection. The performance and weight differences in the three different primary armament candidates can be modeled. The possible exclusion of tank KE protection for this mission role may or may not be deemed acceptable in an unmanned system to maximize the deployability advantages of the Class II platforms vice the additional weight of moving up to the Class III platforms to obtain this level of force protection. Operational modeling (e.g., Combat 21) can be conducted on all three Direct/Indirect fire concepts to assess the relative mission effectiveness resulting from the different levels of lethality and force protection performance inherent in each platform/technology approach. Tiering these platforms will instill weight-based discipline and trades relative to required capabilities.

Summary

This plan focuses on identifying the current material science S&T limitations, and developing Army investment recommendations to enable a future 30-ton IFV and 35-ton MBT in 2030 with similar capabilities and functionality of the current systems. This need for a lightweight combat vehicle force stems from the need to enhance expeditionary capabilities and project long distance military power while retaining and extending Army operational reach and agility. We assessed how close the current state-of-the-art research, development and associated S&T investments could get us by 2030. We are working across the Army, OGAs, industry, and academia to focus light-weighting S&T investments and decisions. This was accomplished through RDECOM-wide working group discussions, review of prior lightweight material studies, and a capstone lightweight material workshop where community experts outside of the Army were asked to highlight gaps in the current S&T portfolio. Because there exist different material needs across the vehicle platform, the S&T investments were broken into four sections: Armor & Structure, Automotive / Mobility, Armaments, and Electronics / Sensors / Other. The overarching recommendations for the Army in the area of Design are as follows:

Design

1. Immediate and continuing investment in, and programs like, Materials in Extreme Dynamic Environments (MEDE) for creating a materials on demand and by design paradigm and providing input to Integrated Computational Materials Engineering (ICME) programs utilizing ballistic materials.
    - Knowledge of the physics of deformation and failure under ballistic and blast loads developed under MEDE will enable the Army to create validated/verified predictive capability for materials response in blast and ballistic environments.
    - Of importance is the integration of manufacturing techniques along with the improved understanding of fundamental physics and specific loading conditions of sub-components. These S&T investments will help the Army develop specific materials to meet specific loading needs for specific vehicle components. Such precise knowledge of materials and loading needs are crucial for the application of light weighting design methods and weight-savings techniques. While some subsystems of ground vehicles are well defined, others currently lack the understanding needed to drive a weight optimized solution.
    Continued development of canonical models to permit the difficult technical problems to be broken down into the scientific phenomena of most importance in a manner that can be more efficiently studied than an actual military design (e.g., how materials fail vs. how an armor package performs). This not only addresses the scientific portion of the problem, but also facilitates sharing in an unclassified format that permits the Army to tap into new sources of knowledge that may not be part of the Army's traditional industry base.
2. Immediate and continuing investment in building an Army core competency in design optimization for weight reduction using commercially-available design tools.

- Design optimization will enable component designs to be tailored to the advanced materials derived through the ICME process.
- Packaging envelopes could be reduced and thus so could weight and cost
- We need to understanding our loads and optimizing existing components. Weight reductions of 10-20% in the automotive industry are typical for any component considered (e.g., Abrams road arm is a solid cross-section and could achieve approximately 50% in weight savings via Finite Element Analysis [FEA]).
- Geometry and material (both informed by manufacturing processes) are intimately connected and cannot be separated.
- Significant weight savings are possible with current materials, and if more advanced (and expensive) materials and manufacturing were used, these could potentially be cost-neutral when cost assessments are made at the vehicle level instead at the sub-component level.
- Design optimization will enable component designs to be tailored to the recoil loads of the system.
- Commercially-available and advanced materials could be utilized in the appropriate places with designs based on manufacturable geometries.

3. Investigate the relevance of Operational Energy models & metrics, and use if warranted, to better understand the impact or outcome of light-weighting materials and design strategies. At minimum, we need to have and maintain an understanding of the major breakpoints or trades that couple with weight in deployment, employment and sustainment footprints of the Army. Couple these results with life-cycle cost metrics to support the development of long term metrics that convey the long term advantages of lightweight combat vehicles. These metrics can then be used to evaluate candidate technologies for integration and to focus cost-effective light-weighting R&D investments.
   - This enables the quantification of metrics that will drive R&D investments towards solutions that will cost effectively reduce vehicle weight.

4. Incentivize Program Management Offices (PMOs) to encourage lightweight technology insertion on currently-fielded platforms prior to the formal identification of a requirement. This change from current practice will reduce risk to new systems and accelerate material and manufacturing development. Cost metrics developed for weight reduction, along with the future return on investment will drive the threshold for determining whether or not to integrate lightweight technologies early. In the case of Boeing (aerospace industry), the team found that the science of lightweight technologies could be advanced by integrating some technologies before being supported by a business case. This allowed the industry to increase confidence in the lightweight technology and speed adoption..
   - Technology and materials can be proved out on systems in the field instead of waiting for major vehicle development efforts. This reduces risk to the new systems and accelerates development.
   - Provide and promote the opportunity for using prototype demonstration vehicles and experimental laboratory-demonstrations to drive technology advancement. This

includes virtual and/or experimental components, systems, and assemblies of systems for the purposes of assessing assemblies of multiple low TRL laboratory concepts or low TRL concepts mixed with higher maturity systems. Investments in these demonstrations will drive the implementation risk of new technologies down and lead to the vehicle concepts adopting “major changes” incubated from a clean sheet of paper.

5. Utilize current real-time tools to engage the User on fielding of new technologies and designs. The User involvement should be beyond personnel engagement and include toolsets with the ability to assess the impact of individual or combinations of low TRL concepts on the end item performance and combat effectiveness from a user perspective. One example of this is the use of a data-interface exchange model such as a Computer Assisted Virtual Environment (CAVE) to provide a real-time concept review in combination with operation/maintenance assessments made by the User.

While not specifically focused on materials, the design recommendations are absolutely necessary if the weight reduction goals set by the Army are to be met in 2030. Industry has applied similar design optimization approaches, metrics, and early technology insertion processes into their weight-reduction programs. We can learn from the auto industry, which understood its vehicles' loads and component designs, and was able to begin implementing the above approaches 20-25 years ago. Thus, these four recommendations must be applied in the Army S&T investments near-term to enable other investments in materials and manufacturing to be executed smartly. The design optimization process enables the informed selection of material and manufacturing research by defining required material volumes and properties, which can then be balanced against the cost metrics for weight reduction.

Certain materials were also identified by each of the Working Groups based on their sub-system requirements and loading conditions. Although specific alloys and composite compositions are not identified, families of materials were selected as being the most promising for enabling weight reduction in a future combat design. What was highlighted by the various discussions, was that current Army, government, and automotive material investments meet the current state-of-the-art families of materials.[20] Again, what is missing in the Army today is the ability to define specific loads, material parameters, and design optimization parameters to be able to invest in specific materials. Without this knowledge, a material cannot be engineered to meet a certain solution and we are stuck with general families of materials. Thus, the below recommendations for material research within the Army is to generally remain as is, until we have the tools to better define our components.

Materials

Armor / Structure

1. Maintain current material research S&T investments in the near term and leverage work in the ICME and design optimization arenas to define future investments.

- Metals – Next-generation alloys (Ultra-High-Strength Steels, Aluminum, Titanium, and Magnesium), Nano-crystalline alloys, dual-hard materials.
- Ceramics – Next-generation ceramics for opaque and transparent armor, ductile deformation mechanisms.
- Composites – including carbon nano-tubes and graphene.
- Polymers.

Automotive / Mobility

2. In conjunction with the design optimization programs, the Army should leverage the materials being developed within the automotive industry and DoE VTO in the near term.
    - Assess how much weight reduction these materials will enable and use the design optimization to guide military-specific alloys; Investigate operational energy models and metrics to develop cost metrics for lightweight materials and technologies.
    - Metals – Al, Mg and Ti Alloys, Gen III HSS, Eglin Steel, TRIP Steel.
    - Ceramics – Wear- & Impact-Resistant Weld-on Coatings.
    - Composites – Resin Composite w/Metal Alloy, Al/SiC, Multi-metallics, Fiber-Reinforced Nylon, Fiber-Reinforced Rubber, Nanofluids and Advanced lubricants, Al/Diamond, Boron Nitride, Carbon fiber Al composites, CNT and Graphene composites.
    - Polymers – Advanced polymers for energy storage (e.g., capacitors) , Urethanes.

3. The Army needs to ensure that advanced technologies such as HSUs, cooling systems, and power plant designs also incorporate weight reduction through material optimization at the component level.
    - Also include alternative approaches such as engine downsizing and waste heat recovery.

4. The Army needs to invest in far-term automotive / mobility alternatives such as fuel cells and advanced suspension designs.
    - Identification of the next big propulsion system, or system layout, that is viable for the Army.
    - Currently, the 30- to 35-ton weight goal will have to be met using a tracked system. What would it take to enable a wheeled, hybrid, or alternative approach with equivalent mobility? (Initial tests indicate this is possible - Republic of Korea Multiple Launch Rocket System and US Marine Corps Marine Personnel Carrier)

Armaments

5. Develop a program to assess the state-of-the-art in ceramics / CMCs, and determine if it is possible to develop the technology for gun bores in the required time frame.

6. Continue S&T investments in energetic material programs to facilitate smaller munitions with similar energetics to current ammunition and higher P_h and P_k.

- Low-Cost Hyper-Accurate Weapons (LCHAW)
- Disruptive Energetics & Propulsion Technology (DEPT)
- Lethal & Scalable Effects Technology (LSET)
- Next Generation Close Combat Missile (NGCCM)

7. Continue investment in the advanced manufacturing of Nextel 610 fibers in cast aluminum matrices on steel gun barrels.
    - Research challenges with keeping the steel substrate below its thermal soak temperature, formation of intermetallics at the interface, and galvanic corrosion between Al MMC and steel parts.
    - This manufacturing advancement would enable lighter gun barrels and other components across the vehicle system.

Electronics / Sensors / Other

8. Continue to invest in vehicle architecture consolidation efforts.
    - Metals / Semiconductors – CNTs, Graphene, SiC (all would reduce power requirements and could increase operational temperature).
    - Novel Electronics – Conformal / integrated components, flexible displays and multi-function sensors will enable new packaging designs that are more compact, thus reducing the under-armor volume.
    - Alternate Power Generation – Harness shock compression motion from the vehicle to power small sensors or electronics to reduce the power distribution cables.
    - Share Processing Capacity – In conjunction with common architecture and elimination of electronics redundancy, enable multiple electronics packages to share common power and processing capacity to reduce power consumption and packaging space.

In addition to design processes and materials, manufacturing technology recommendations were identified in support of design optimization and advanced material development. Although not specific, the general idea of having manufacturing development in parallel with material development is critical to transitioning any component to the field. Although Army S&T investments currently support manufacturing and joining of materials, we must ensure that we have manufacturing programs in place to support the emerging materials going forward. Therefore the key recommendations in manufacturing are:

Manufacturing

1. Increase investment in joining and advanced manufacturing technologies for emerging materials through ManTech and other manufacturing avenues where external (industry, OGA, academia) investments fall short.
    - Require high-potential emerging materials to have supporting joining and manufacturing programs.

- These programs will be driven by the materials developed through the ICME and material research programs.
- To enable earliest material transition, the manufacturing programs must be executed early on and in parallel to the material development program that they support.
- A portion of the ManTech investments should be tied to long term strategy and strategically determined by the COT as opposed to driven by an annual investment competition.

2. The Army must become an active voice in the NNMI hubs and provide the requirements of the Army to the consortia as derived from ICME and design optimization programs.
    - Enables cost sharing and development of a manufacturing base that can support the Army's future needs

Applying all of these recommendations, and assuming current estimates for advanced material performance, the potential weight reduction for a future MBT and IFV was calculated for 2030. The projected weights for these systems were roughly 45-49 tons and 29-31 tons respectively. While the future IFV met the weight reduction goal of 30 tons, this still assumes a great deal of risk on research programs. Unfortunately, 45 tons is far above the goal of 35 tons for a future MBT when only material science solutions, processes and technologies are applied. Additionally, while all of the assumptions made in this weight analysis represent the maximum weight reduction for high risk S&T investments, much of the actual weight reduction values will be driven by vehicle design/application, future threat sets and the cost of these advanced materials and technologies. Even with every high risk investment materializing by 2030, in order to meet the 35-ton goal, a series of technologies that would require a clean sheet vehicle design approach, along with some operational doctrine changes. Some of these technologies design options from the NGCCV study were briefly discussed. However, to fully assess what the future MBT weight would be with the given requirements of this study, a complete vehicle design would have to be executed. This could be rolled into the Army's Future Tank study.

Resolving Other Obstacles to Weight Reduction

The barriers to lighter-weight combat vehicles are significant and more than simply technological. Many, such as the long acquisition cycle, the reactive nature of the defense market as compared to the proactive nature of the commercial market, and the risk aversion toward the introduction of new technologies, are beyond the scope of this report. However, there are several other items that can be done to help improve the possibility of these weight-reduction solutions being transitioned to current and future vehicle platforms, which have also been highlighted by previous reports.[21] While there is a lot of potential in weight-reduction itself, the solutions ultimately must be transitioned to a fielded system to be successful. The following suggestions should be considered now to enable future programs to successfully shed weight.

1. Utilize an existing Army-wide governing body with a Board of Directors (BoD) to ensure purposeful focus on light-weighting Army combat vehicles. Examples include the Council of

Colonels, Warfighter Technical Council or the Combat Vehicle BoD. We recommend the Combat Vehicle BoD.

- The BoD shall be independent of any program of record (POR) or organization and should include representatives from the User, S&T and acquisition communities including TRADOC, MCoE, ILSC, PEO GCS, and RDECOM.
- The BoD will ensure high-level engagement and participation in the National Network on Manufacturing Innovation (NNMI) hubs, and work to ensure that the hubs provide value for the Army. NMMI hub engagement is also expected to help reduce the 7- to 10-year window between material development and transition, by helping the material developer community understand physical requirements during the development process. The BoD's first task shall be to establish a charter, including how they will ensure that industry materials, manufacturing, design methods, and joining investments are leveraged to the maximum extent possible for use by the Army.
- The BoD will establish a Cross Organizational Team (COT) to execute the recommendations within this plan. Specifically this team will focus on developing the Army's design optimization process, and coordinate with all relevant Army programs to ensure that the process works for each vehicle subsystem and component. This includes the decomposition and understanding of fundamental physics for each vehicle sub-component-level component and their individual loading requirements. This team will also be responsible for coordinating/developing the metrics that are mentioned next; COT must ensure that metrics are approved and adopted by the evaluation community. The COT will also focus on synchronizing lines of effort with tangible targeted milestones in both research and concepting. These milestones should capture technical achievements along with establishment of draft user requirements and assessment approaches, even if they are several years from formal implementation. It is important that the community have this concrete and agreed upon frame work and baseline plan to work with, given the necessary changes that will occur as we proceed.

2. The BoD and COT will establish light-weighting metrics and promulgate them through Army R&D and acquisition programs throughout the vehicle lifecycle. This will enable system-level design trades that must consider weight as a design requirement, resulting in reduced vehicle weights. Overarching recommendations:
   - The BoD will make decisions on trades (e.g., weight vs. performance) in accordance with proposed technology maturation timelines and lightweight metrics as proposed in the plan as decision points.
   - Ensure the value of weight savings always exists in the technical evaluation criteria and the requirements used by Source Selection Evaluation Boards (SSEBs). The BoD will evaluate methods to achieve this goal; one potential method would be to offer a cost bonus to the contractor for weight savings, the amount of which should be reflective of the Army's value of weight savings as determined by the developed metrics.

- The use of forward-looking Systems Engineering practices and tools helps to avoid the Defense OEM practice of knowingly trading weight savings for other requirements, as mentioned in some private discussions with Defense OEMs. Specifically:
  - Maintain weight as the primary focus and not trade weight for performance.
  - Use or Develop operational metrics to determine the relative benefit of weight savings on operational performance of the vehicle versus other performance criteria such as transportability/ton, fuel consumption/ton, fording/ton, and reliability/ton.

3. Leverage TARDEC's CVP effort as a pilot project to develop cost-informed light-weighting metrics
   - This could be accomplished while optimizing current components by making only small changes to the system (ex: hollow spindle requires different bearings and hub, but may require the same space claim). This approach would help to build design confidence for the User and technical community by providing significant risk reduction, and enable the quantification of potential weight savings for a 2030 IFV and MBT as was intended by convening the LCVSTC Materials Conference.

4. Shorten and thrift the materials and manufacturing development processes.
   - Currently, new materials can take in excess of 7-10 years to transition. Per workshop sub group discussions, this is in part due to the development process which starts with a company or academic institution developing a material in absence of a specific application. By taking the actions in recommendation 2, the Army could provide better information to material developers and become involved in the development process earlier, and ideally reduce the transition timing for new materials.

5. Show value of weight savings in design requirements.
   - The value of weight savings must always exist in the evaluation of the requirements used by an SSEB. To achieve this, we recommend that a cost bonus be offered to the contractor, the amount of which should be reflective of the Army's value of weight savings. If the weight is reduced below the threshold requirement, a certain cost per pound benefit, derived specifically for that system, could be given to the contractor in evaluation by the SSEB.
   - Unless a strategy such as this is implemented, once the weight goal is met by the Offeror, OEMs and Offerors knowingly begin to trade weight savings for other requirements because there is no benefit for them to pursue weight reduction. This was mentioned in some private discussions, and is also occurring on current JLTV vehicles where they are moving from expensive lightweight aluminum components back to cast iron to be more cost competitive. Cost-weight reduction metrics per component may push themselves out of the affordability range, yet cost-weight reduction metrics averaged across a sub-system or vehicle may prove to increase affordability while driving some amount of technology acceptance and drive lighter weight components into vehicles.

Finally, as a holistic approach to light-weighting, the following graphic (Figure 21) illustrates how the Lightweight S&T Recommendations (i.e., Plan) can tie into advanced operational and concept models, along with work from the PMs to provide a holistic Army approach to weight reduction. The lightweight approaches, advanced concepting, and operational models could then direct future vehicle studies and NGCCV iterations to determine the variables that will enable the Army to become more expeditionary.

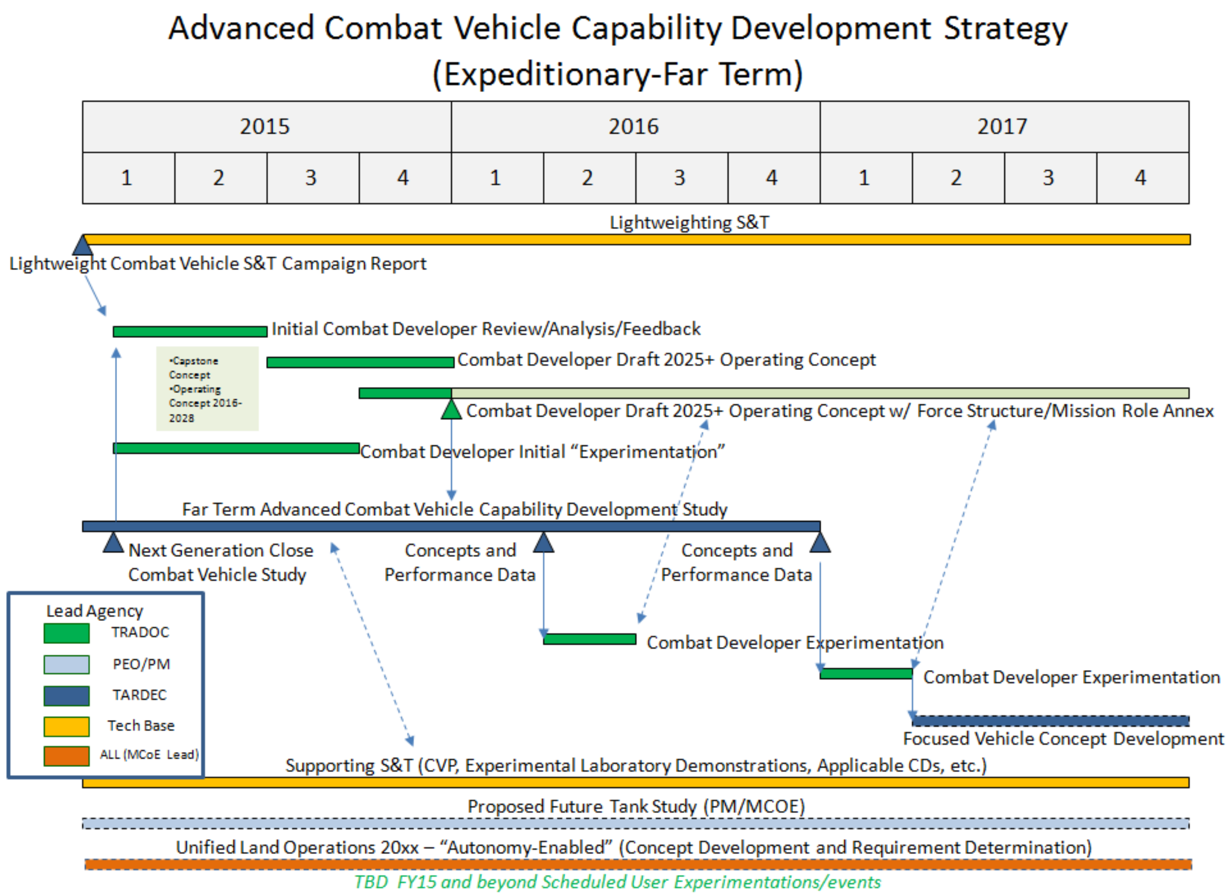

Figure 21. Advanced combat vehicle capability development strategy.

The chart below (Figure 22) shows the establishment of a Board of Directors (BoD) to govern the recommendations in this report and to optimize S&T investments across the five overall light-weighting lines of effort (Armor & Structures, Automotive / Mobility, Armaments, Electronics / Sensors / Other, and non-material science approaches to light-weighting). The BoD will also establish the COT to execute the recommendations within this plan. Overarching Army design optimization and ICME investments are also laid out, along with the top level investment areas and general weight savings for each vehicle subgroup. The weight reduction estimates include current S&T investments and the recommended S&T investments.

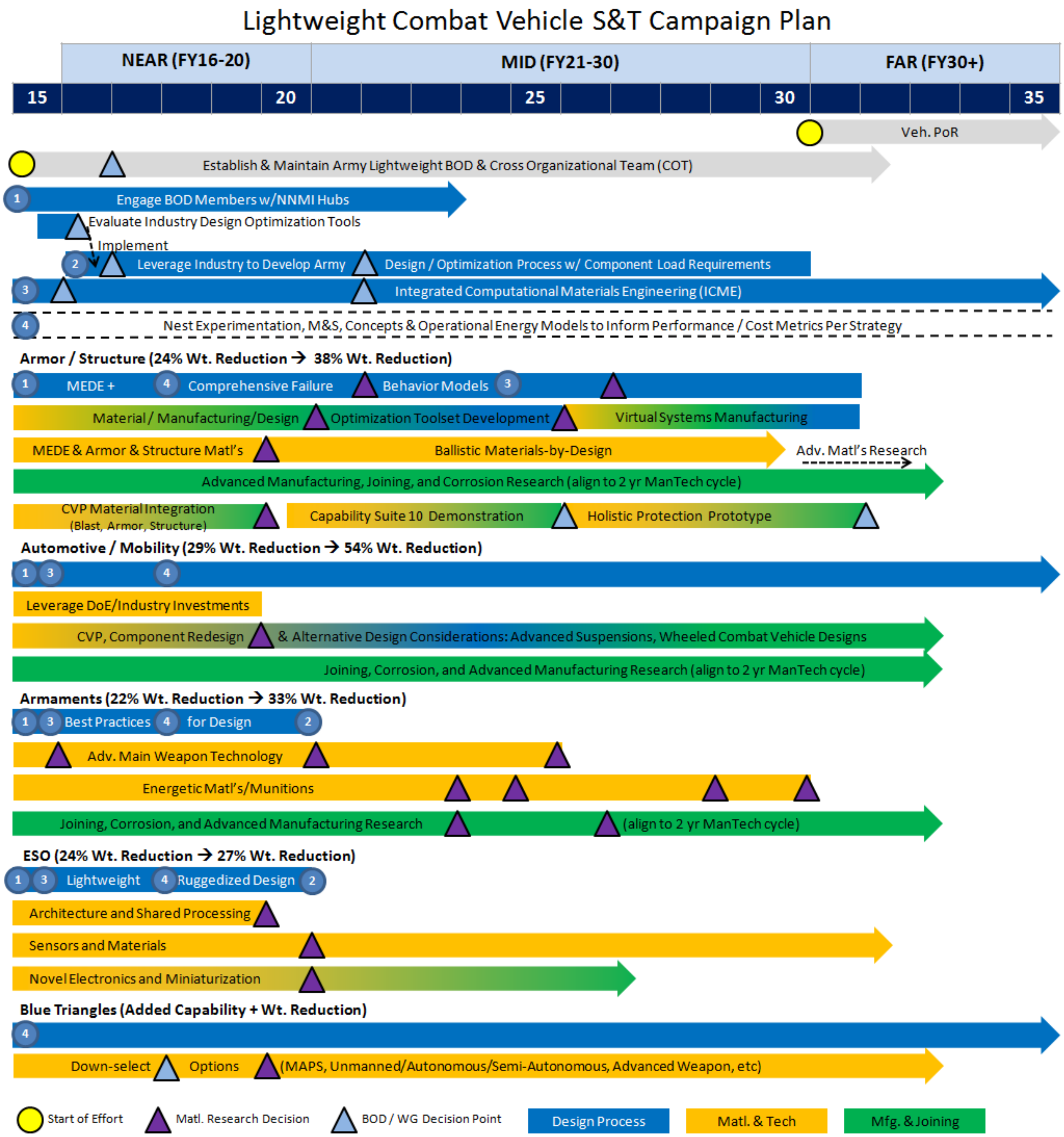

Figure 22. Lightweight Combat Vehicle S&T Campaign Plan overview.

Appendices

Appendix A: Lightweight Combat Vehicle Science & Technology Campaign - Team Charter

Purpose

Identify S&T programs both internal and external to the Army that include reducing vehicle/component weight as a payoff in an effort to define the Army's S&T plan for future vehicle systems. These programs can either focus on traditional weight reduction (i.e., material replacement) or weight mitigation/avoidance (i.e., design characteristics that result in weight reduction such as adaptive protection systems). However, all programs considered should have a direct application to Army Ground Combat Vehicles with either current or future requirements in mind. The goal of this effort is to define an S&T plan for the Army that leverages efforts across the research community in lightweight systems, and how the path forward will support the goal of 25% (IFV) to 47% (HCV) weight reductions in ground vehicle systems by 2030.

Background

Over the years, materials research has led to more mass efficient armor solutions for ground combat vehicles (e.g., 60% KE armor weight reduction over 30 years). However, constantly emerging threats on the battlefield have led to increased protection requirements, which have caused vehicle weights to steadily increase. Today, 70 to 80 ton platforms are required to protect our soldiers from increasing threat sets. In order to keep these vehicles moving through the battlefield, a large logistics tail is required. Thus, 2/3 of the Army personnel strength is needed to support the remaining 1/3, composed of combat arms personnel. Therefore, future combat vehicles need to have not only a balance of mobility, firepower and protection, but they must also be significantly lighter to restore strategic responsiveness.

Towards this end, the Army S&T community has the challenge of identifying a research path towards creating future combat vehicles that are at least as capable as those today, but with a fraction of the weight. In order to successfully accomplish this mission, research programs in the areas of material science, manufacturing, joining/assembly methods, vehicle and weapon design/architecture, and weight mitigating/avoidance technologies (e.g., APS, Adaptive Protection, etc.) must all be investigated and integrated into a cohesive plan. Without manufacturing and joining/assembly programs to support the material science programs, new materials with attractive properties will not be able to be integrated into a vehicle solution. Additionally, while material substitution requires the least amount of change in how the Army builds and uses the vehicles, vehicle design and/or threat engagement and their corresponding weight benefits should be equally investigated.

Figure A1 illustrates the need to have a holistic approach for weight reduction. Armor and structure account for 54% of the vehicle weight on a current M1A2 SEP, so naturally the typical response is to

focus weight reductions in that area. However, to meet the desired 47% vehicle weight reduction by 2030, the armor and structure could only account for 5.3 tons using this mentality. Unfortunately, 5.3 tons of armor and structure will not be sufficient to provide the necessary level of protection in the foreseeable future. Looking at what is possible by 2030, current material science research suggests that there is a potential of reducing the armor and structure weight by up to 30% while keeping protection levels the same. Unfortunately, even with this dramatic reduction in armor and structure weight, the vehicle weight is at most only reduced by 17%. In order to approach the goal of a 47% vehicle weight reduction, reductions in each of the subsystems must be investigated.

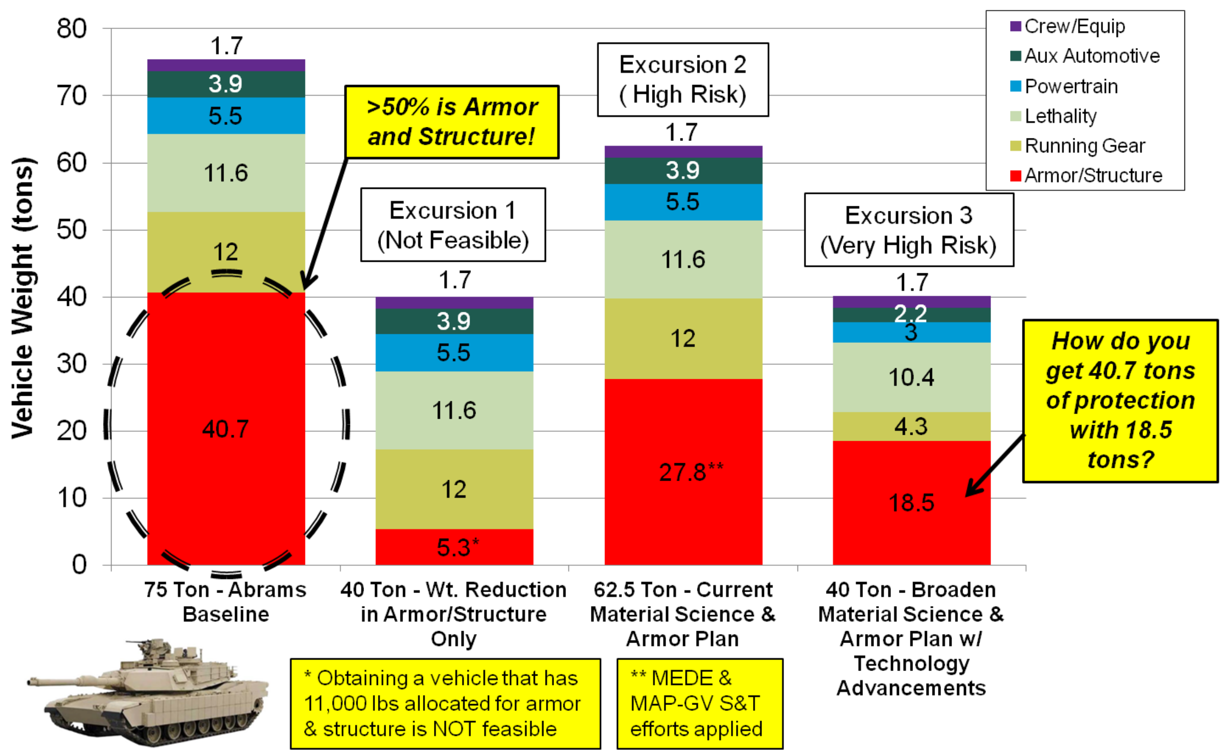

Figure 23. Weight breakout of a fully equipped M1A2 SEP highlighting the challenge of weight reduction.

Traditional armor weight reduction is only part of the equation. In the event that material science alone cannot accomplish the desired weight reduction, use of vehicle design, threat engagement technologies, and automated systems can provide additional weight saving potential. Vehicle weight reduction on this scale is a whole vehicle, multi-technology endeavor that requires no stone to remain unturned.

Scope

This is a nine month effort (January 2014 – September 2014) focused on identifying current and future S&T programs that can be applied to Army combat vehicle weight reduction. Programs of interest include material science, manufacturing, joining/assembly methods, vehicle design/architecture, and weight mitigating/avoidance technologies in all areas of vehicle performance (i.e., mobility, survivability, lethality, etc.). The team will identify relevant programs across the government offices (not just DoD), academia and industry for inclusion into a cohesive weight reduction plan for Army combat vehicles.

The information gathering process will culminate with an information meeting/workshop hosted by the team, from which a report documenting the S&T plan for the Army will be assembled. This report will highlight not only the programs currently being planned or executed, but also the gaps that need to be filled in an attempt to drive towards the weight reduction numbers desired by 2030.

Below is a list of high level goals that the team must accomplish:

1. Identify internal and external (i.e., Army, Navy, Air Force, DoE, DARPA, NSF, NASA, NIST, etc.) S&T programs that provide system/component weight reduction and could be applied to the goals for combat vehicle weight reduction.
    - These programs will include material science, manufacturing, joining/assembly methods, vehicle design/architecture, and weight mitigating/avoidance technologies.

2. Collect data on schedule, cost benefit, materials, weight reduction potential, etc. for each program.

3. Identify areas of the vehicle where each technology could be applied in order to accurately assess the vehicle weight reduction potential.

4. Organize the programs into a plan diagram that indicates the leveraging of efforts and how the materials/technology transition through TRLs.
    - Identify gaps in current S&T plan and high impact areas of research.

5. Host information meeting/workshop w/invited speakers throughout the lightweight community.

6. Document Army S&T plan to address the desired 2030 combat vehicle weight reduction in a formal report
    - Answer how far material science alone will reduce the weight
    - Answer how far we can take the weight reduction using all avenues of design and S&T

Team Empowerment

No additional authority should be necessary for this effort. However, each organization will utilize their chain of command should the need arise during the collection of information.

Team Operations

Each organization POC has the ability to add/remove members within their organization, but continuity and schedule for the project must be maintained. All content of the final S&T plan document will be reviewed by each core member listed in Section 4, with the final approval resting with the SES members of each organization. As a working level team, communications should be frequent and open, but formal monthly meetings will be organized by the TARDEC POC.

Acquisition Milestones and Schedules

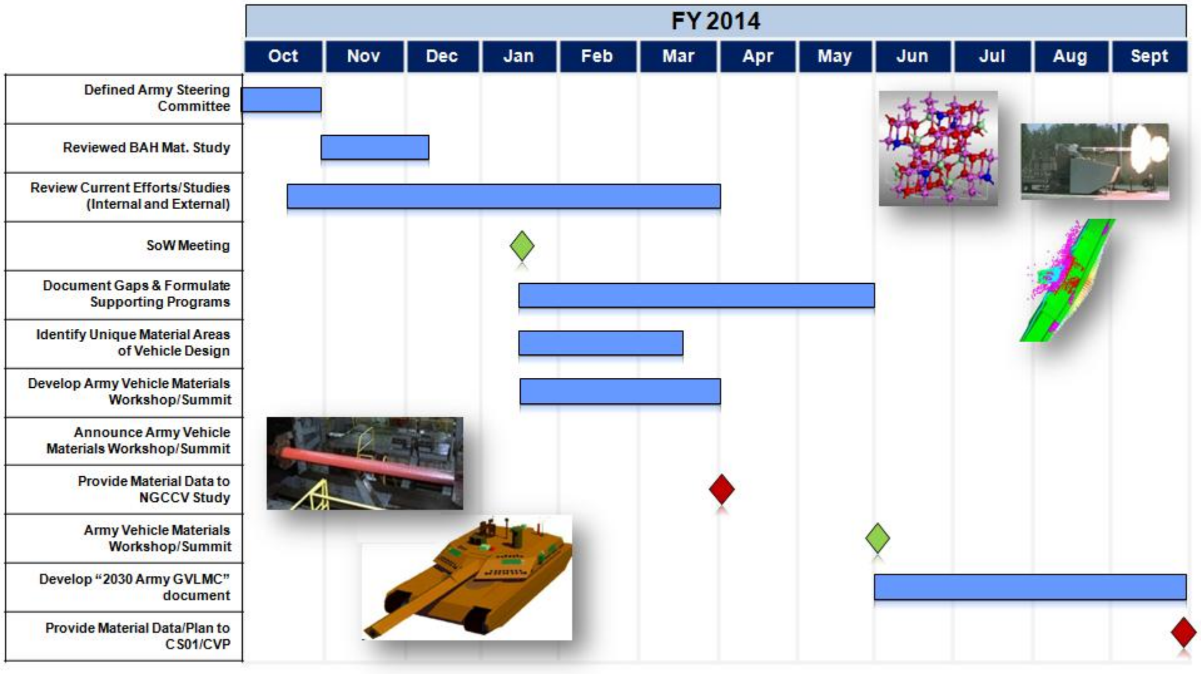

Figure 24. LCVSTC schedule.

Appendix B: Workshop Participants

Approximately 100 people participated in the workshop. The participants represented a cross-section from industry, academia, Army and other government agencies. Participants were purposefully selected from companies that are considered to be innovative, and most typically do not currently perform significant amounts of work with the Department of Defense, if any. The breakout of participants is shown in Figure B1, below. Note that while the number of Army participants appears large, 51% of these were event staff and speakers.

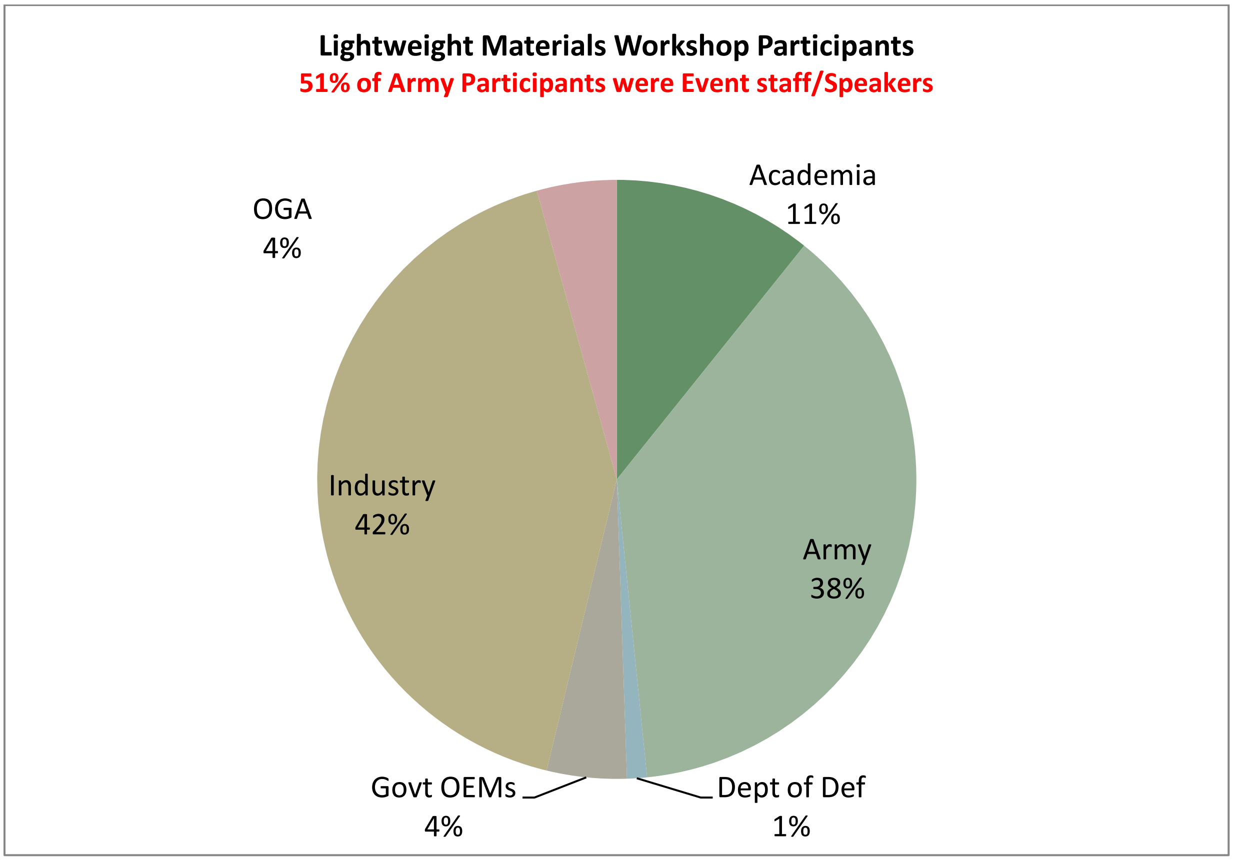

Figure 25. Lightweight Materials Workshop participant analysis.

Appendix C: Disclaimer

Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Dept. of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoD, and shall not be used for advertising or product endorsement purposes.

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